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Pouring the 1·5-t medium-frequency induction furnace used for making cast iron at the foundry of Messrs Georg Fischer AG., Schaffhausen

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THE MEDIUM-FREQUENCY INDUCTION FURNACE FOR MELTING STEEL, GREY IRON AND NON-FERROUS METALS

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The medium-frequency induction furnace is ideal for melting special steels in steel-foundries and has also proved excellent in a number of installations for melting grey iron and non-ferrous metals. The metal is heated by the inductive effect of an alternating magnetic field passing through the charge; the field is generated in a copper coil. The present article describes the principle and design of m.f. induction furnaces, having particular regard to the standardization of the various types, and concludes with a detailed description of the installation supplied to the steel-foundry at Georg Fischer AG. in Schaffhausen.

THE introduction of the medium-frequency (m.f.) melting furnace, the first of its kind to employ the principle of induction heating in foundries, took place over 40 years ago. Together with the mains-frequency furnaces, the construction of which was commenced about 20 years ago, they have proved extremely reliable and, taking advantage of the operational experience gained, have been developed into mature, modern units.

The m.f. furnaces are mainly employed in steel-foundries as they are ideal for melting special alloyed steels. Since the specific power which can be transmitted to the furnace charge can be made higher at elevated frequency than at mains frequency, the m.f. furnaces are notable for their short melting times. They can be used with advantage when the alloy is frequently changed, starting from cold without any liquid charge.

The design developed by Brown Boveri for m.f. furnaces will now be described and a summary given of the standardized sizes of furnaces.

Principle

The metal to be melted is placed in a crucible of ceramic material or graphite, in which there is an induction coil fed with alternating current. Owing to the physical phenomenon in which the passage of an alternating current through the coil induces voltages in the metal inside the coil, in this case the furnace charge, thereby creating eddy currents in the metal, the magnitude of which is governed by the electrical resistance of the metal, the metal becomes heated according to Joule's law and is brought rapidly to its melting point.

In order to produce a sufficiently high current in the melt or in the individual pieces forming the cold charge, the metal must have certain minimum dimensions on the one hand, while attention must be

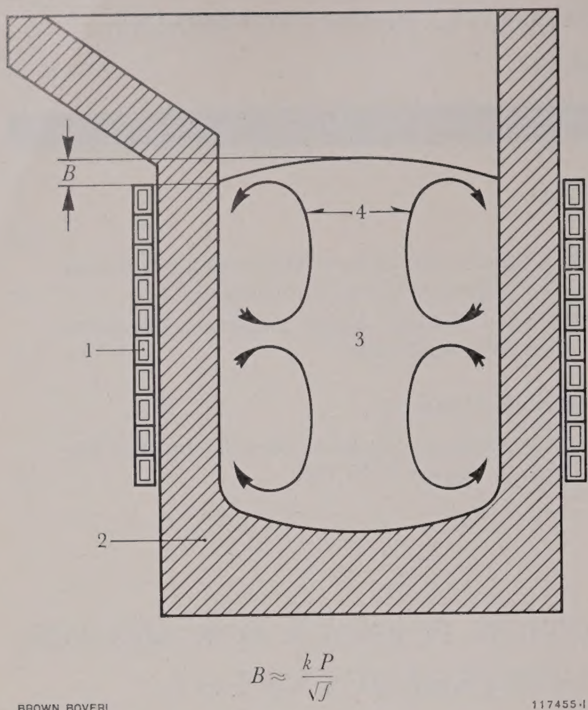


Fig. 1. – Stirring effect in the molten metal in an induction furnace

1 = Induction coil
2 = Ceramic crucible
3 = Molten metal
4 = Direction of movement
B = Camber
P = Power induced in the coil
f = Frequency of the induced current

TABLE I

Minimum size of pieces of various metals used as cold charge in induction furnaces with no liquid charge, shown in terms of the frequency

Frequency c/s / Metal	500	1000	2000	4000	10 000	Diameter or min. thickness
Grey iron and steel	80	55	40	28	20	mm
Aluminium	30	20	15	10	6	mm
Copper	25	18	12	6	5	mm
Brass Silver Gold	35	25	18	13	8	mm

paid to the internal diameter of the crucible on the other. At medium frequencies in the range from 500 to 10 000 c/s, when using a ceramic crucible, the size of the pieces of the cold charge should not be less than the figures given in Table I opposite. Pieces of the sizes tabulated are usually available as scrap material in almost any foundry.

In certain cases the cold charge, without any liquid residue, may consist of pieces of sheet with smaller dimensions than those given in the Table, but attention must be paid to the special method of charging, the melt-down time being extended owing to the smaller power consumption.

A further characteristic feature of the induction furnace is the stirring action of the melt. Due to the simultaneous occurrence of the alternating magnetic field in the axial direction of the coil and the induced current in the melt, electrodynamic forces are produced which endeavour to displace the molten metal axially out of the coil, thus giving rise to the well-known stirring action occurring in all induction furnaces, as illustrated in Fig. 1.

This stirring action is greatly appreciated from the metallurgical point of view because local overheating is almost completely avoided and the melt is allowed to mix well with the added alloying ingredients. But, when superheating, the stirring effect must not be too violent, otherwise the slag may break off and pieces of slag or oxide skin may fall into the molten metal, or increased gas absorption may occur, possibly accompanied by burn-up of the alloying elements. If the stirring effect is too vigorous, especially with high pouring temperatures, the durability of the crucible suffers owing to the constant wear.

The camber of the melt due to the stirring effect, as given by the formula in Fig. 1, depends, on the one hand, on the power induced in the melt and, on the other, on the frequency of the induced current. Given the same kind of crucible and with equal induced power, the camber decreases with rising frequency or, in other words, when a current of higher

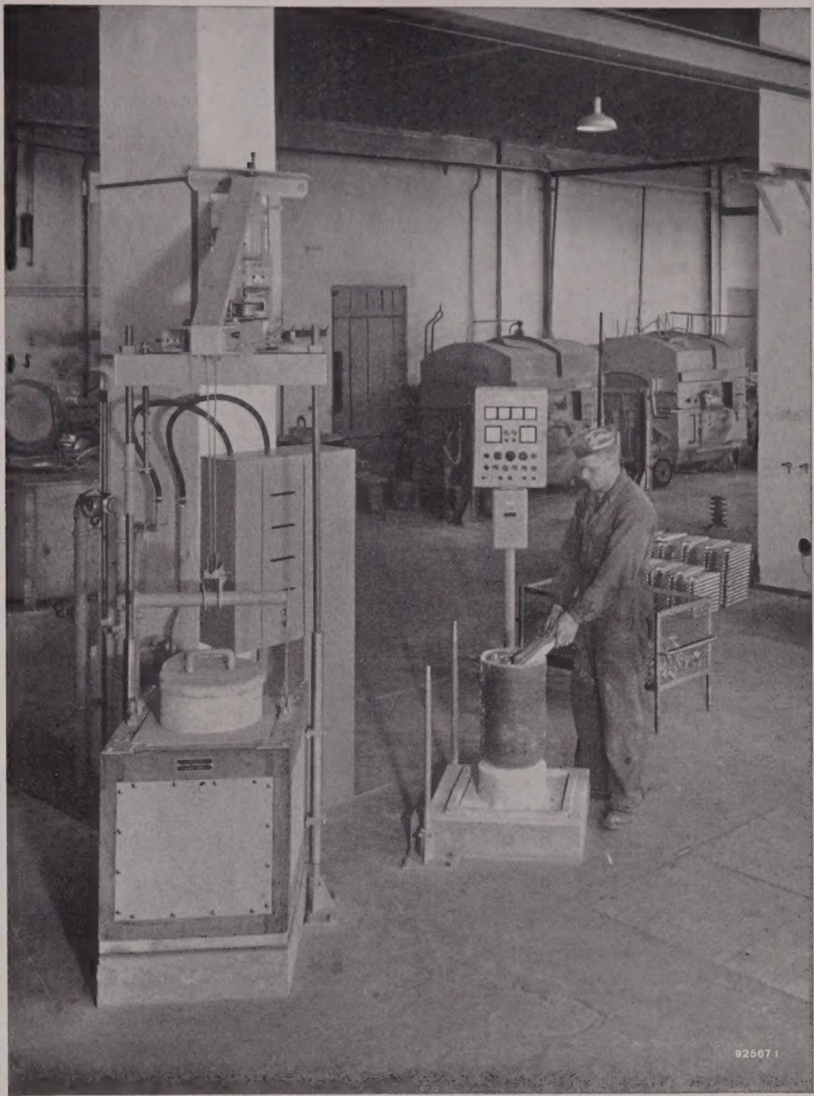


Fig. 2. – Bell-type m.f. induction furnaces used for melting light alloys to supply liquid metal to 14 resistance-heated holding furnaces in the course of day

Generator output 100 kW at a frequency of 2 kc/s; different kinds of alloys can be melted successively, a charge of 40 kg being available for pouring every 15–16 minutes.

TABLE II

Comparison between melting rate and melt-down time for bulky charge without liquid charge for constant stirring of the melt in terms of the frequency of the induced current for a furnace with a capacity of 2·5 t of grey iron

Frequency c/s	Melting rate appr. t/h	Melt-down time appr. min
50	1	150
500	4	40
1000	5·5	30

frequency is used with the same camber, higher powers are admissible and, in consequence, higher outputs or shorter melt-down times can be attained than with current of lower frequency. Table II shows the relationship for three frequencies.

Design of the Medium-Frequency Induction Furnace

Depending on the sphere in which they are applied, the medium-frequency furnaces can be grouped into two distinct types: the bell-type furnaces and the tilting furnaces.

Bell-type induction furnaces are primarily used for light and non-ferrous metals up to a maximum crucible capacity of about 100 kg. Fig. 2 depicts a furnace of this type with a capacity of 70 kg of aluminium. The metal to be melted is in a graphite crucible, while the actual furnace, or to be more precise the induction coil, is suspended on a pivoted arm and is lowered over the crucible to melt the charge. The advantage of this arrangement is that metal can be poured direct from the crucible, without changing to a ladle first, with the accompanying loss of heat. More often than not, in order to keep the electrical equipment fully occupied, work is carried out at two points, as in Fig. 2. While the melting process is under way in the left-hand furnace, the crucible on the right is being freshly charged.

The tilting induction furnaces have a robust welded metal frame in which the induction coil is incorporated. The crucible is embedded in the coil and may be either of graphite or rammed material. The furnace can be tilted about the spout on a pair of bearings, as shown in Fig. 3, the smaller furnaces being movable by hand with a crank-handle and wire-rope winch, while the larger units are equipped with a pair of strong oil-hydraulic tilting cylinders controlled by manually operated valves, the speed of tilting being variable over a wide range. To reduce the loss of heat by radiation from the surface of the melt, the furnace is covered with a thermally insulated cover, which can be closed by hand in the smaller models. For the larger furnaces, with capacities of 500 kg and over, the cover is operated hydraulically by a manual control valve, enabling it to be swung out with ease. In the middle of the large pivoted cover is a small sliding lid, the smelters being thus protected against the full radiation when they have to draw off

Fig. 3. – Pouring steel from a 500-kg m.f. induction furnace

The furnace is tilted hydraulically, controlled from the unit at the side by means of a manual control valve. The furnace cover can be swung to the side by the same means.

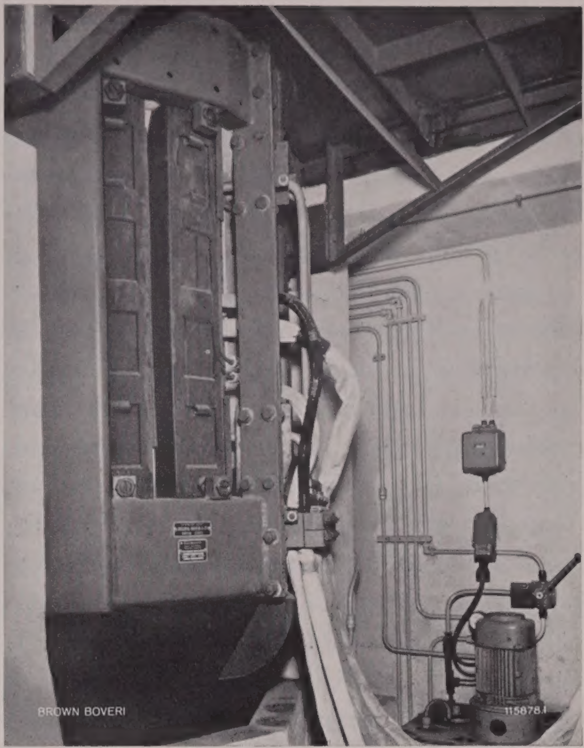


Fig. 4. – View of a 1·5-t m.f. induction furnace for steel, showing the water-cooled cables, allowing power to be supplied even when the furnace is tilted

Bottom right is the vertically mounted motor driving the pump in the oil reservoir.

samples, measure the temperature, or add alloying ingredients.

The induction coil is fed through water-cooled cables, allowing power to be supplied while the furnace is tilted. The oil-hydraulic unit comprises an oil reservoir with a built-on vertical screw-type pump driven by a three-phase motor. The main supply cables and the oil-hydraulic unit can be seen in Fig. 4.[1]

To dissipate the unavoidable heat conducted through the walls of the crucible and the heat generated by the passage of current through the induction coil, the latter is made of hollow conductors, through which a current of cooling water is continually passed. If the available water supply is not sufficiently clean or too hard, a closed-circuit cooling system can be provided, with a pump as shown in Fig. 5. To prevent the coil from being damaged in the event of the power supply to the pump failing, for instance, an emergency water supply must always be provided, such as an emergency water-tank.

Preparation of the Crucible

For grey iron the best results have been obtained (except in a few cases) with an acid quartzite ramming mass consisting of 99 % SiO_2 with the addition of 0·5 to 2·4 % of boric acid as sintering medium, the percentage varying with the pouring temperature. For steel both acid and basic linings, or a neutral rammed mass have proved successful.

When melting steel, high pouring temperatures are usually stipulated, in which case the crucible must be composed of a basic or neutral rammed mass, whose softening point at elevated temperature is higher than

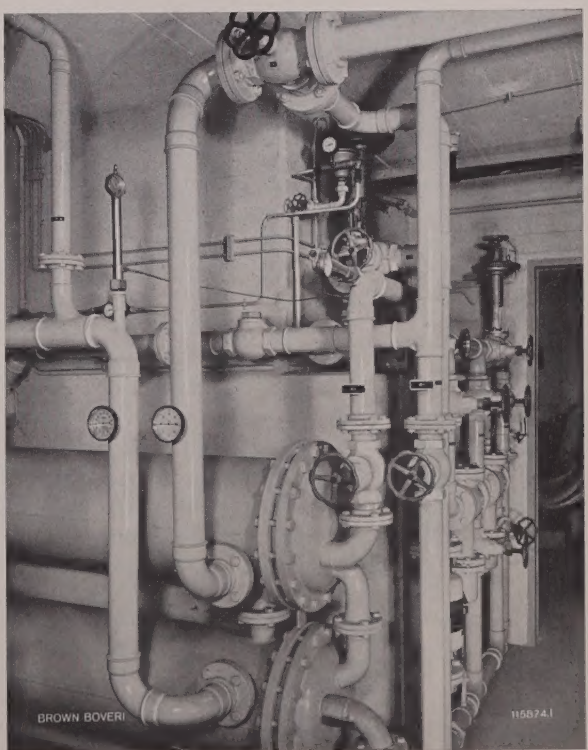


Fig. 5. – Closed-circuit cooling system for the water cooling the furnace, the capacitor bank and the m.f. converter

[1] Fig. 4, 5 and 10–15 were made available by courtesy of Messrs Georg Fischer AG., Schaffhausen, Switzerland.

that of an acid material. The basic lining also permits certain metallurgical processes, such as desulphurization and dephosphorization, to be carried out at least to a small extent. However, it must be pointed out that effective slagging cannot be performed in an induction furnace because the slag itself is relatively cold and thus slow to react chemically. The resistance to abrasion of the basic crucible is not so good as that of the acid refractory. But since the movement of the melt in the m.f. furnace in practice is less than that in the mains-frequency furnace, the durability of the basic lining is still economical. Very good results as regards durability have been obtained with a neutral refractory containing zirconium, although this material is considerably more expensive.

To melt metals with a low specific electric resistance, such as gold, bronze, aluminium, etc., it is common practice to use a graphite crucible. Owing to the resistance of the graphite being much higher than that of the metal, the power transmission is very efficient, the current induced in the crucible wall in this case heating the actual crucible. The metal to be melted is thus largely heated by conduction from the crucible.

Planning and Standardization of Medium-Frequency Induction Furnace Installations

The standardization of medium-frequency induction furnaces and the associated installations greatly simplifies the task of planning the layout of a furnace plant. It arose out of the requirements of industry and practical experience gained with previous installations.

Tables III, IVa and IVb summarize the various data of the tilting m.f. induction furnaces which have been standardized by Brown Boveri. The figures

TABLE III

Frequency in c/s					Type ISM	Approximate crucible capacity for:					
10	4	2	1	0·5		Steel Grey iron kg	Aluminium kg	Copper kg	Brass kg	Silver kg	Gold kg
					0·002	2	0·7	2·4	2·4	2·8	5
					0·0035	3	1·1	4·2	4·2	4·9	8·8
					0·005	5	1·7	6	6	7	12·5
					0·01	10	3·5	12	12	14	25
					0·015	15	5·2	18	18	21	38
					0·025	25	8·6	30	30	35	64
					0·05	50	17	60	60	70	125
					0·1	100	35	120	120	140	
					0·16	160	55	190	190	225	
					0·25	250	87	300	300	350	
					0·5	500	175	600	600	700	
					0·75	750	260	900	900	1050	
					1·0	1000		1200	1200	1400	
					1·5	1500					
					3·5	3500					
					4·5	4500					
					6	6000					

shown for melting rate apply to newly lined hot crucibles, operating continuously with a cold charge of such a nature that mean power consumption during melting down is at least 90 % of that of a furnace filled with liquid metal.

A m.f. installation comprises the m.f. converter with its associated starting gear, the induction furnace with its capacitor bank for improvement of the power factor, and the control gear cabinet. The arrangement is shown in the circuit diagram (Fig. 6a).

Since lining a rammed crucible always takes a certain time to complete, during which production is inevitably interrupted, the arrangement in Fig. 6b is recommended, in which two furnaces are employed instead of one, the connection to the busbars being made by a double-throw isolator, and the capacitor bank being also common to both furnaces. This arrangement assumes, of course, that both furnaces are of the same capacity.

If the capacities of the two crucibles are different, the arrangement shown in Fig. 6c is recommended, each furnace being equipped with its own set of capacitors. Moreover, this system offers the advantage of allowing the double-throw isolator to be dimensioned for a lower current as only the active current has to be taken into account.

If, instead of a double-throw isolator, contactors are employed which are operated from a control board, the operation can be so arranged that one furnace is used for melting down while the other is only connected to the supply for brief intervals to keep the molten metal hot. This method of operation allows a quantity of molten metal to be prepared, equal to the sum of the capacities of the two furnaces.

If the intention is to plan an installation which can be extended later, to consist of several converters and furnaces, it is advisable to choose the arrangement in Fig. 6d. The m.f. equipment then comprises several

TABLE IVa

Steel						
Furnace type	Frequency	Mean furnace power	Crucible capacity	Melting and superheating rate up to 1600 °C [1, 2]	Power consumption [2]	Melt-down time with solid charge and cold crucible
ISMS	c/s	kW	kg	kg/h	kWh/t	h
				appr.	appr.	appr.
0·002	9600	14	2	13	—	—
0·0035	9600	15	3·1	17	—	—
0·005	9600	23	5·1	29	—	—
0·01	9600	25	10·5	27	—	—
0·015	9600	25	15·5	25	—	—
0·025	9600	35	27	37	—	—
0·05	2050	70	52	100	960	0·9
0·1	2050	140	105	220	850	0·9
0·16	2050	175	170	280	830	1·1
0·25	1025	210	270	345	790	1·25
0·5	1025	325	550	580	750	1·45
0·75	1025	375	800	670	730	1·75
1	1025	505	1050	890	720	1·7
1·5	1025	635	1600	1170	710	1·85

TABLE IVb

Grey iron						
Furnace type	Frequency	Mean furnace power	Crucible capacity	Melting and superheating rate up to 1450 °C [2]	Power consumption [2]	Melt-down time with solid charge and cold crucible
ISMG	c/s	kW	kg	kg/h	kWh/t	h
				appr.	appr.	appr.
0·05	2050	65	50	100	890	0·85
0·1	2050	145	100	255	760	0·7
0·16	2050	170	165	300	750	1·1
0·25	1025	200	260	365	700	1·2
0·5	1025	305	525	590	670	1·4
0·75	1025	425	765	840	660	1·4
1	1025	505	1000	990	660	1·5
1·5	1025	595	1530	1220	630	1·8

[1] Melting rate for grey iron (1450 °C) in furnace type ISMS is about 4 % higher than for steel.

[2] Melt-down and superheating time in continuous operation with hot furnace, without initial liquid charge, using pieces of at least the size shown in Table I, not counting the time spent in charging, deslagging, alloying, pouring and holding.

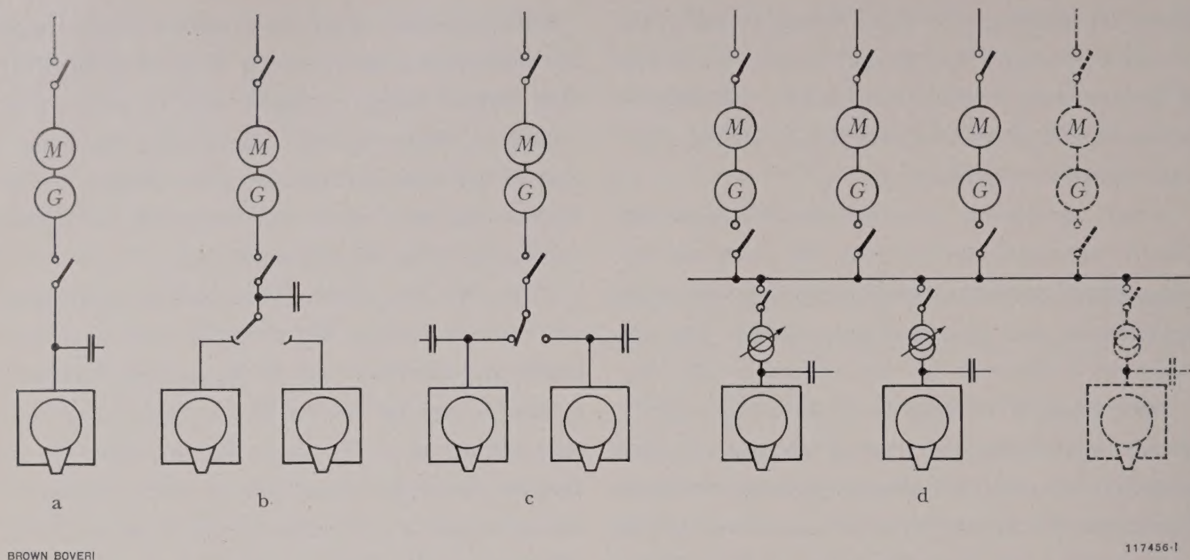


Fig. 6. – Circuit combinations for m.f. induction furnaces

For notation see text.

converters, whose generators feed a common set of busbars. The individual induction furnaces can then be connected to the busbars as required, the task of power regulation being performed by a water-cooled m.f. transformer. Each furnace has its own capacitor bank. The capacity of the furnaces may be different, in which case the power is controlled separately for each. With this layout it is also possible to provide the arrangement in Fig. 6 b for each furnace. This arrangement of the plant allows it to be extended at will, simply by adding further m.f. converters of the same size and furnaces with their associated tap-changing transformers and capacitors.

To give some idea of the space occupied by m.f. furnace installations, Fig. 7 and 8 show layout plans for typical plants with different types of furnace, assuming the circuit layout conforms to Fig. 6a.

Layout of a Completed Installation

The following description refers to a completed induction furnace plant, arranged according to Fig. 6c, and installed in the steel-foundry of Messrs Georg Fischer AG., Schaffhausen, Switzerland. It has altogether four induction furnaces with a total power of 1600 kW at 1 kc/s. According to the specification, facilities had to be provided for simultaneous melting in two furnaces each with a capacity of 0·5 t of steel, together with one furnace of 1·5 t capacity, while a fourth furnace holding 100 kg was to be used for melting experimental charges intermittently. The three larger furnaces are equipped with their own m.f. converters and capacitor banks, whereas the small furnace, while having its own capacitors, does not have a converter of its own. Depending on whether an 0·5 or the 1·5-t furnace is momentarily out of action, the 0·1-t furnace can be connected to the idle converter by a selector switch.

Fig. 9 shows the electrical arrangement of the installation, while Fig. 10 is a view of the plant showing all four furnaces. The motors driving the converters are all fed from the 380-V mains, each group of four motors having a separate transformer for connection to the 10-kV system. The transformers are disconnected from the system in a switchgear cell, each having its own airblast circuit-breaker and a manually operated isolator (Fig. 11).

In order to avoid the inrush surge in the supply system, the converter motors are started in star-delta in an automatically controlled sequence. This ensures that the starting current only rises briefly to about

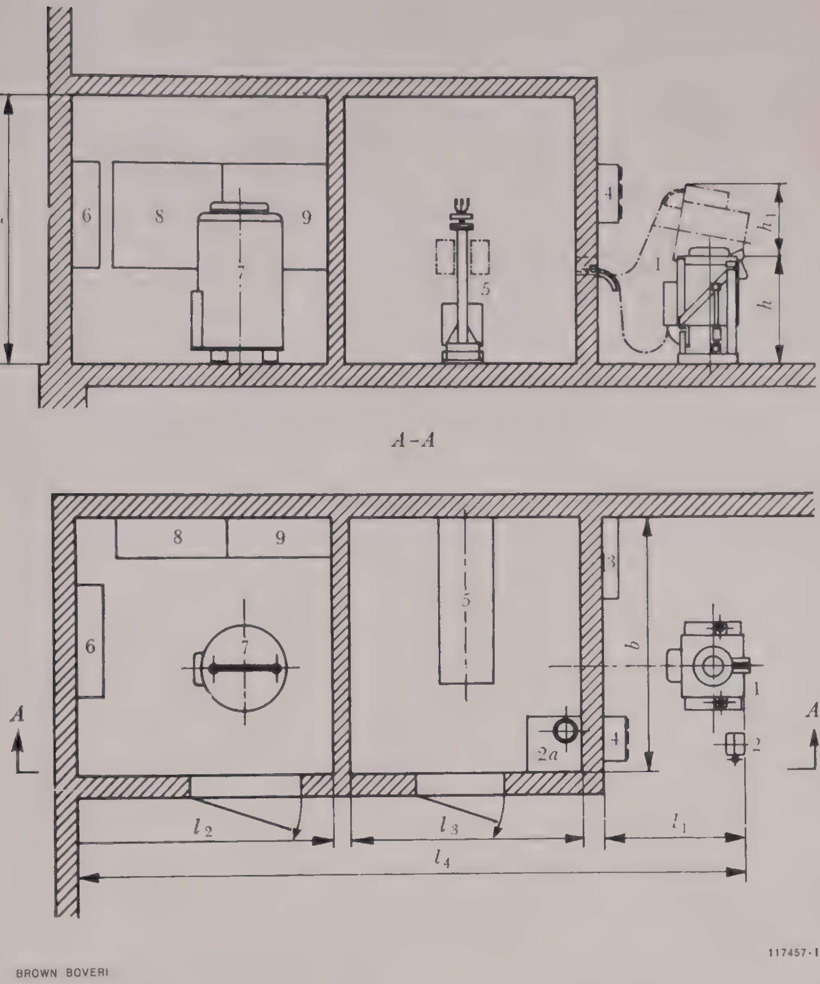


Fig. 7. – Layout of a m.f. induction furnace installation types ISM 0·05–ISM 0·16

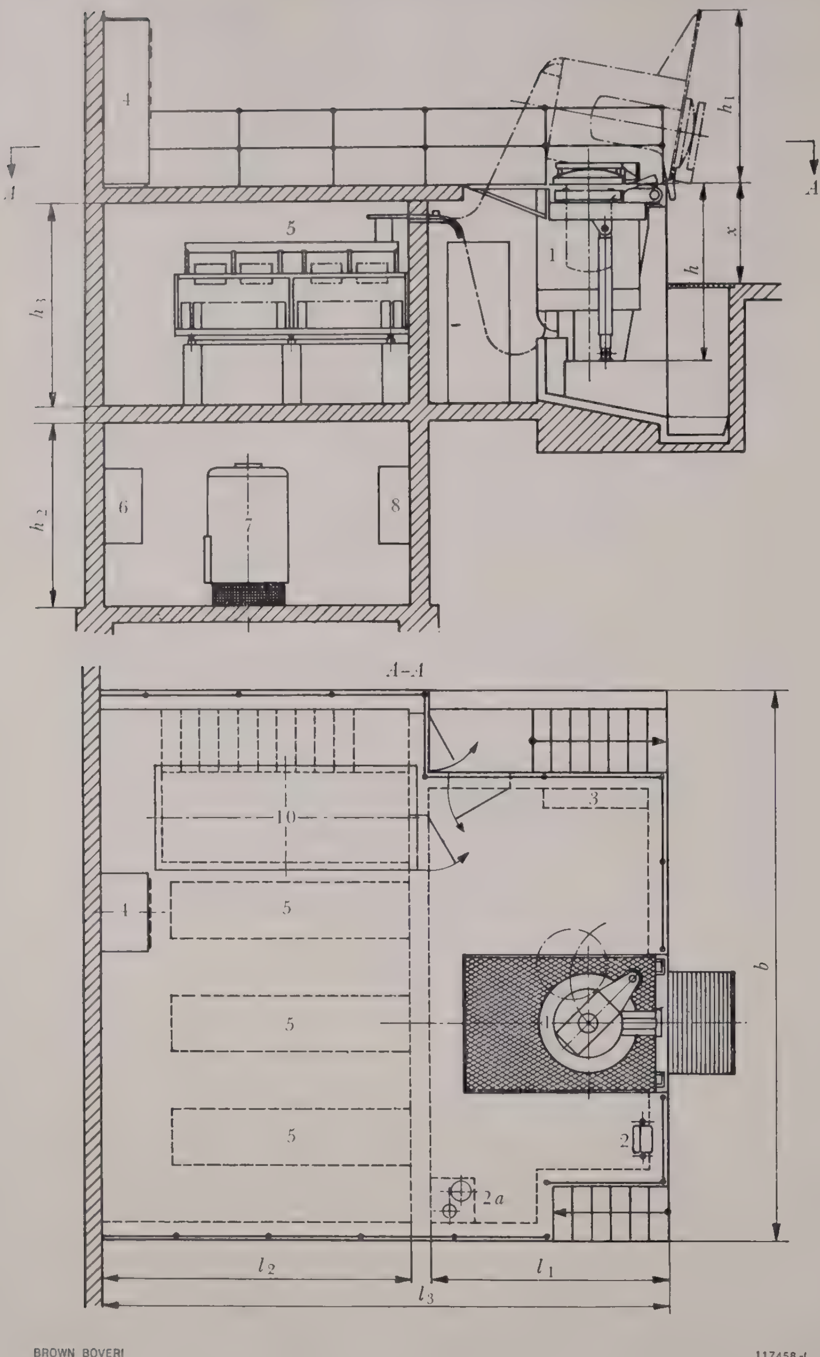
1 = Medium-frequency induction furnace
2 = Control unit
2a = Motor-driven pump for pressure-oil
3 = Annunciator panel for the cooling water
4 = Control board
5 = Capacitor bank
6 = Starting gear for m.f. converter
7 = Medium-frequency converter
8 = Control gear for m.f.
9 = Power factor regulator for the m.f. system

Dimensions in mm

Type ISM	b	h	h_1	h_2	l_1	l_2	l_3	l_4
0·05	2300	970	630	2400	1280	2300	2100	6000
0·1	2700	970	730	2400	1400	2700	2400	6820
0·16	2700	970	850	2400	1530	2700	2400	6950

twice the rated current. The contactors for the starting system are accommodated on a welded angle-iron framework designed on the unit construction principle, so that each converter is allocated a section of its own.

The change in the resistance of the furnace, due to the reduction of the wall thickness of the crucible as time goes by, is duly allowed for in this installation by dimensioning the converters so that they can give the full rated output between 80 and 110% of the rated voltage. The excitation unit employs thyratrons with automatic limitation of the current and the voltage, enabling the generator to produce the full output in the above voltage range. With the aid of the potentiometer fitted in the control board it is possible to vary the m.f. power infinitely. The excitation unit referred to (see Fig. 13) automatically keeps the voltage at the induction coil constant. The same unit limits the generator current to the permitted level by reducing the excitation current.



Type ISM	b_1	h	h_1	h_2	h_3	l_1	l_2	l_3
0·75	5800	2000	2100	2400	2400	2500	4000	6750
1·0	7100	2200	2200	2400	2500	2850	4000	7100
1·5	7100	2300	2300	2400	2600	3100	4000	7350

Fig. 8. – Layout of a m.f. induction furnace installation types ISM 0·75–ISM 1·5

The height x of the platform will vary with the method of pouring or the size of the ladle. Notation as for Fig. 7.

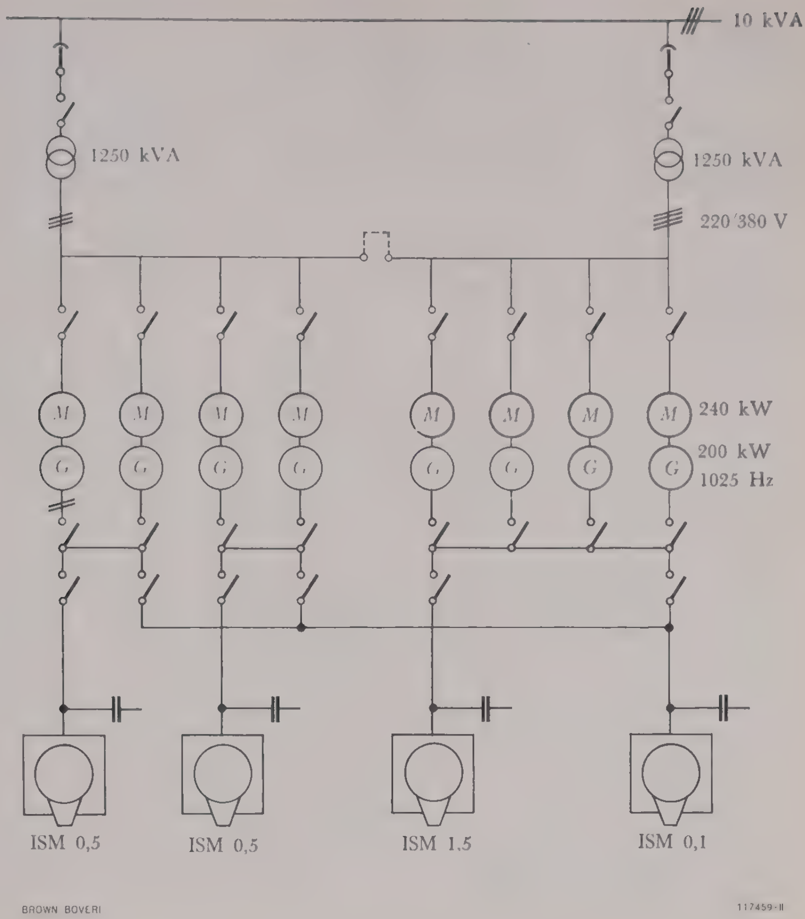


Fig. 9. – Arrangement of the electrical installation for a melting plant for steel with a total power of 1600 kW at 1 kc/s

With 2 induction furnaces each holding 500 kg, 1 furnace holding 1·5 t and 1 holding 100 kg

M = Motor of the m.f. converter
G = Generator of the m.f. converter 1025 c/s

To balance the reactive power of the furnace there is a capacitor bank allocated to each furnace, as illustrated in Fig. 14. Owing to the relatively poor power factor of the induction coil, a considerable amount of reactive power has to be produced. To accommodate the necessary capacitors in as small a space as possible, water-cooled elements are used, mounted with their stepping contactors in self-supporting angle-iron frames. The automatically controlled power factor correction relieves the furnace operators of the task of switching the capacitors on and off during melting.

The supply of cooling water for the induction coils and the water-cooled m.f. converters is provided by a closed-circuit cooling system (Fig. 5). The water heated by the losses in the furnace and converters flows through a heat exchanger where the heat is transferred to a raw-water circuit. There is no need to specially treat the raw water for this purpose as impurities are easily removed from the heat exchanger. The advantage of this system with a closed cooling circuit and a heat exchanger is that deposits of chalk or impurities, as well as corrosion, are avoided in the induction coil, the cooler of the converter and in the piping. For safety reasons the pump circulating the cooling water in the closed circuit is augmented by a reserve pump, which can be selected from the control board by means of a switch. If, in spite of this precaution, the flow of water should be interrupted, for instance due to a power supply failure, ordinary water from the mains is automatically fed direct into the cooling circuit by an electrodynamically operated valve.

All branches of the cooling-water circuit are monitored by flow relays and the outlet temperatures checked by thermostats. Should the desired rate of

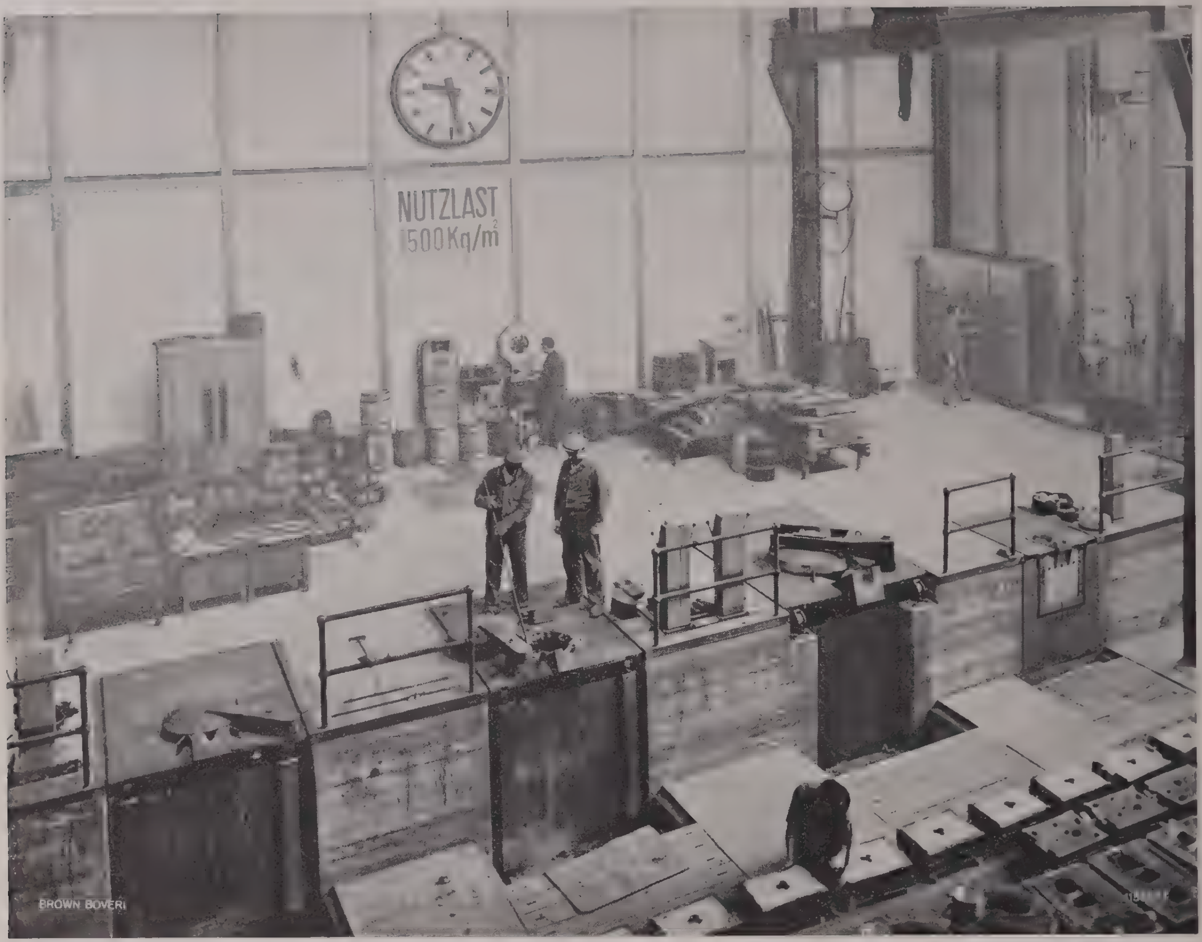


Fig. 10. – Plant with four m.f. induction furnaces with a total power of 1600 kW, installed at Georg Fischer AG., Schaffhausen

Right, in the background, is the control board for the four furnaces.

Fig. 11. – High-voltage cells belonging to the furnace installation shown in Fig. 9 and 10

comprising one metering cell in the middle and two switchgear cells, each containing an airblast circuit-breaker and an on-load isolator.

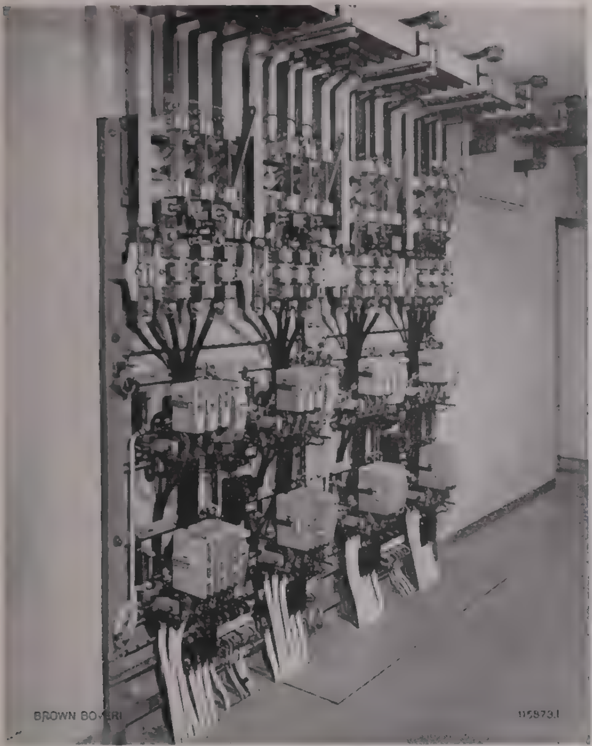


Fig. 12. – Control gear for successive star-delta starting of four m.f. converters

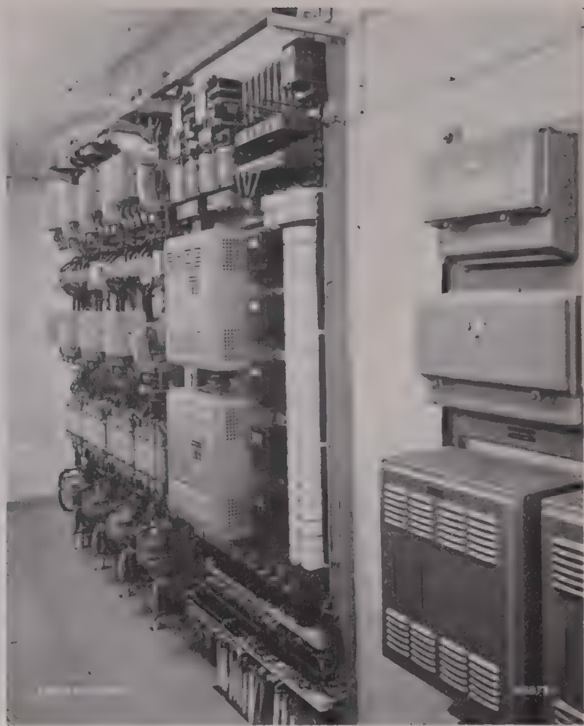


Fig. 13. – Control gear for the generators of four m.f. converters, containing the contactors connecting the generators to the busbars and the shorting contactors, also the electronic exciter unit with automatic voltage control, electronic current limitation and power control

On the right is the equipment for automatic power factor control.

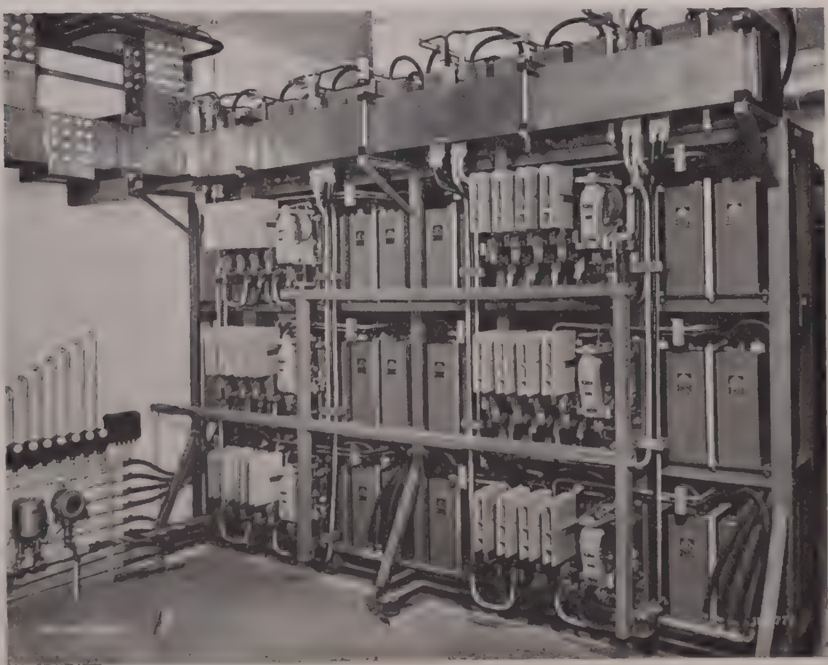


Fig. 14. – Capacitor bank for improvement of the power factor of the induction coil, comprising water-cooled elements combined with their stepping contactors to form a compact unit

On the left of the picture can be seen the thermostats and manostats used to keep a check on the cooling-water circuits.

Fig. 15. – In the same room as the racks containing the control gear are the eight m.f. converters

Each of these converters is a water-cooled machine of the vertical monobloc type, rated 200 kW, 1025 c/s.

flow not be obtained, or the outlet temperature of the cooling water be too high, the affected part of the installation is immediately disconnected from the supply. An audible alarm warns the smelters of this stoppage, the nature of which is indicated by an annunciator.

To open the covers of the three larger furnaces, and to tilt the body of the furnaces, there is a control unit next to each furnace, from which the corresponding oil pump is actuated by pressing a push-button, being controlled by a manual control valve (Fig. 10). The speeds of the two movements are infinitely variable. The control unit also contains an emergency button by which the furnace concerned can be immediately disconnected.

All the switchgear, including the auxiliaries, is mounted beneath the furnace platform in two separate storeys, as shown in the sectional elevation in Fig. 8. In the event of a crucible collapsing, there is a pit below the platform to catch the molten metal and convey it to a sump of the same capacity as the crucible.

The machine room, in which the cooling-water pump and the heat exchanger are accommodated, is immediately beside the 1·5-t furnace space, i.e. below the 100-kg furnace space. The oil-hydraulic pump for each furnace is located in the furnace space, on a raised plinth at one side. Should one of the pumps fail, there is a standby pump available, which can be connected into the corresponding oil circuit by means of a manual control valve. During the installation of the apparatus and piping for the cooling-water and oil systems, special stress was laid on neat layout and easy access for the operating staff.

Immediately behind the three furnace spaces in the upper floor of the basement is the room containing the water-cooled capacitors (Fig. 14). The connection between the furnaces and the capacitors,

which are mounted with the stepping contactors in a welded angle-iron framework, is made by water-cooled cable, thus facilitating the supply of reactive power when the furnace is tilted.

In the lower basement are the eight converters with their switchgear for the motors and generators (Fig. 15), as well as the high-voltage equipment. To each group of four converters there is a transformer stepping down the high voltage from 10 kV to 380 V, and rated 2250 kVA, 50 c/s. This arrangement with two transformers was chosen to allow the plant to continue operating at reduced power in the event of one transformer becoming defective. This possibility was also taken into account in the installation of the low-voltage busbars, in that, should such a fault occur, the two busbar systems can be connected together (see also the circuit diagram in Fig. 9).

In the same room as the frequency converters are the contactors and other control gear for the generator circuits which, like the starting contactors, are mounted in angle-iron frames designed on the unit construction principle. The excitation units for power control and the automatic power factor control gear are accommodated in a special section of the frame.

In conclusion it is worth pointing out that Brown Boveri have so far successfully commissioned more than 160 m.f. induction furnaces. The valuable experience gained with these installations has continually been exploited for further development and improvement of installations of this kind. As a result, the m.f. induction furnace has evolved into a reliable and indispensable item of modern foundry equipment.

(KME) W. ANNEN

MODERN TRENDS IN OVERVOLTAGE PROTECTION, ESPECIALLY AT HIGH VOLTAGES

621.316.93

When planning the overvoltage protection of high-voltage installations, it is common practice, and justifiably so, to rely on the protection afforded by modern lightning arresters. Apart from limiting atmospheric overvoltages, a lightning arrester is nowadays often expected to protect h.v. equipment against switching surges. The present article describes the effect on the design of an arrester resulting from this stipulation, referring to a new development based on the principle of spark gaps with magnetic blow-out.

Coordination of the Insulation in High-Voltage Alternating-Current Installations

ALL THE latest rules and regulations dealing with overvoltage protection (see, for example, [1, 2, 3, 4, 5]) are based on the level of protection that can be afforded by a modern lightning arrester. As will be known, it is usual to distinguish between three kinds of overvoltage, namely atmospheric overvoltages, switching overvoltages (or surges), and power-frequency overvoltages. Included in switching overvoltages there are also the transients resulting from earth faults, in addition to power-frequency overvoltages caused by changes in the network. Power-frequency overvoltages are the steady-state conditions resulting from the interruption of active or reactive load, especially in connection with long lines, and also steady-state overvoltages caused by earth faults.

Since the magnitude of atmospheric overvoltages bears no relation whatsoever to the line voltage, it is only possible to limit the requirements regarding the dielectric strength of the insulation in the face of voltage surges when there is sufficient assurance that any transient voltage applied to the h.v. equipment will not be permitted to exceed a certain upper limit. This task has always been entrusted to either a spark gap or a lightning arrester, the latter generally affording some important advantages—except under very special circumstances.

Apart from this conventional task, there is an increasing trend nowadays for lightning arresters to be stipulated for the limitation of switching overvoltages. To what extent this is justified will not be dealt with in this article, since non-restriking circuit-breakers are available for the most serious switching operations, such as the interruption of capacitive loads. Nevertheless, it should be pointed out that, according to a recent publication [6], there are numerous possible ways of producing switching overvoltages. Such questions primarily become important when a coordinated insulation is employed in solidly earthed networks.

It is customary to base the characteristic data of a lightning arrester on the r. m. s. value of the maximum line (power-frequency) voltage which may be continuously applied to the arrester terminals. This voltage is defined as the rated voltage, because the arrester, after discharging an overvoltage, must be capable of interrupting the power-frequency follow current against a recovery voltage equal in magnitude to the rated voltage. In insulated networks, or systems earthed through an arc suppression coil, the rated voltage is usually made equal to the maximum phase-to-phase service voltage. In effectively earthed networks, on the other hand, it is possible to make the rated voltage 80 % or even only 75 % of the maximum phase-to-phase service voltage of the system. This then permits a reduced level of insulation to be employed in the station equipment, especially in transformers, without reducing their reliability.

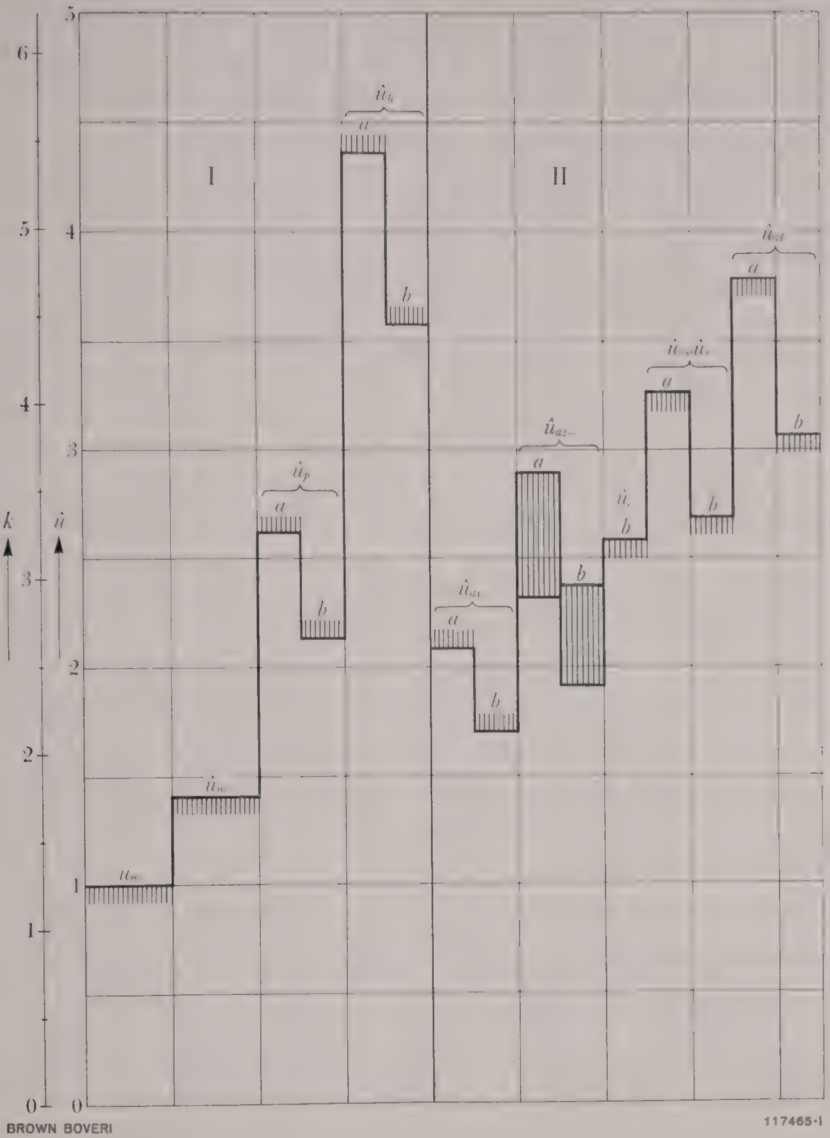


Fig. 1. – Test voltages and maximum sparkover voltages of arresters, as laid down by IEC 71, SEV 0183: 1957, and partly conforming to VDE 0675; also the maximum permissible switching overvoltages according to the recommendations of TC 17 of IEC for service voltages exceeding 100 kV

All values are referred either to the r.m.s. value U_m of the maximum phase-to-phase voltage (ordinate scale $\hat{u}$), or the peak value $U_m \times \sqrt{2}/\sqrt{3}$ of the normal phase voltage (overvoltage factor k). The scale $\hat{u}$ is commonly employed in arrester techniques, the scale k is for assessing switching overvoltages.

I = Service and test voltages

II = Maximum sparkover voltages

$\hat{u}$ = Voltage values referred to U_m

k = Voltage values referred to $U_m\sqrt{2}/\sqrt{3}$

a = With full insulation

b = With reduced insulation

u_m = Relative r.m.s. value of max. phase-to-phase service voltage

$\hat{u}_m$ = Relative peak value of max. phase-to-phase service voltage

$\hat{u}_p$ = Relative peak value of power-frequency test voltage

$\hat{u}_h$ = Relative impulse test voltage (1/50 impulse full-wave)

$\hat{u}_{a1\sim}$ = Relative minimum value of the peak power-frequency sparkover voltage according to IEC and SEV

$\hat{u}_{a2\sim}$ = Relative range of the peak power-frequency sparkover voltage recommended by VDE

$\hat{u}_{as}$ = Relative maximum value of the 100% sparkover voltage

$\hat{u}_r$ = Relative maximum residual voltage at rated discharge current

$\hat{u}_{aF}$ = Relative maximum front-of-wave sparkover voltage

$\hat{u}_c$ = Relative maximum value of overvoltages produced by switchgear operation (under discussion by TC 17 of IEC)

Fig. 1 shows relative values for the test voltages of the equipment (range I) and the voltage limits afforded by arresters (range II). With one exception ($\hat{u}_{a2\sim}$) these values are all contained in the Swiss Rules for Coordination [3], applying particularly to voltages where U_m exceeds 100 kV. The reference value U_m is the r.m.s. value of the maximum phase-to-phase service voltage. Everywhere else the values shown are peak values. On the left are the figures for the power-frequency sparkover voltage and the impulse withstand voltage (full-wave impulse 1/50), shown for full (*a*) and reduced (*b*) insulation. The shading pointing upwards or downwards indicates whether the particular value is a maximum or minimum. Shown in the right-hand half of Fig. 1 are the voltage limits which the arrester has to guarantee. Here too values are given for full and reduced insulation, the meaning being that reduced insulation is permissible when an arrester with a low rated voltage (in the example in Fig. 1 about 80% of the maximum phase-to-phase voltage) can be employed.

The main factors governing the protection against atmospheric overvoltages by arresters are the impulse sparkover voltage, the residual voltage and, to a lesser extent, the front-of-wave sparkover voltage. It can be seen from the diagram, and confirmed by calculation, that the safety margin given by $\hat{u}_h/\hat{u}_{as}$ is approximately 33% which, in most cases, is quite adequate. The situation is rather different when it comes to protection against switching overvoltages. Here the main factor to be considered is the power-frequency sparkover voltage of the arrester. Almost all rules governing arresters (e.g. [2, 4]) only prescribe a minimum figure for this value and thus leave the manufacturers considerable freedom. The opinion has indeed been expressed that it is correct to design the arrester, having regard to its reliability, so that it never sparks over as a result of switchgear operations, i.e. the visualized power-frequency sparkover voltage should be as high as possible.

Today a somewhat different view is taken of this; the VDE regulations [5], for instance, recommend both maximum and minimum values for the power-frequency sparkover voltage. The range permitted by VDE is also shown shaded in Fig. 1. Moreover, to a second ordinate scale, the overvoltage factor k often used to assess switching overvoltages is also given, the reference value of which is the maximum peak value of the phase voltage of the system. It can thus be seen that, according to VDE regulations, for reduced insulation levels the arrester must spark over when overvoltage factor is less than 3.

In Technical Committee 17 (Switchgear) of IEC discussions are at present being held regarding the maximum overvoltages circuit-breakers may be permitted to produce. The tendency is to fix this value, denoted by $\hat{u}_c$ in Fig. 1, at 72% of the impulse sparkover voltage (see also [12]). This value is higher than the upper limit of the power-frequency sparkover voltage stipulated by VDE. Hence it is also apparent that a correctly dimensioned circuit-breaker may be perfectly capable of causing a correctly dimensioned lightning arrester to spark over (see [7]). The consequences arising out of this requirement will be described in the next chapter.

Conditions to be Fulfilled by Modern Arresters

As explained in the preceding chapter, it is customary nowadays to stipulate quite severe conditions for lightning arresters. As far as atmospheric overvoltages are concerned, it was shown that safety margins exceeding 33% can be attained when the values given in Fig. 1 are observed. Today it is feasible and, in fact, often specified that, for a given rated voltage, arresters must be built for a much lower impulse sparkover voltage and residual voltage. Fundamentally speaking, this makes it possible to increase the safety for the arrester by choosing a higher rated voltage, to extend the range of protection, or to reduce the insulation level of the equipment still further. From the economic aspect the last of these is certainly the most interesting, but West European countries are very hesitating in their adoption of this, although it is very widespread in America (see also [8]). It is very important to be

able to lower the insulation level further, particularly for very high voltages, e.g. service voltages of 420 kV or more.

The stipulation that an arrester must also be able to limit switching overvoltages to a certain extent has much more far-reaching consequences than might be expected at first sight. There is then always a possibility that the arrester, following sparkover due to a switching surge, may have to discharge a long overhead line or underground cable. It is stipulated that a lightning arrester must be able to withstand a rectangular wave of 150 A lasting 2000 μs, corresponding to a charge of 0·3 As [2, 4]. But it is an easy matter to check that heavier charges may occur in many cases (consider the example given in [9], for instance), particularly at very high voltages. Thus it often happens that considerably more stringent conditions are laid down by the power undertakings regarding the ability to withstand rectangular waves than are specified in the regulations. For the non-linear resistance element this means that its characteristic must not be too steep, so that the voltage across the resistances during the passage of a rectangular current wave shall not be too high. But in conjunction with the trend towards lower residual voltages, however, this implies that, in an arrester designed to comply with these requirements, heavier follow currents are produced on sparkover than in older arresters. Fifteen years ago an arrester was designed so that the residual current would be of the order of some tens of amperes. With the modern requirements follow currents of several hundred amperes are experienced. To interrupt such heavy currents necessitates the provision of very high-powered sparking gaps. The situation is aggravated by the stipulation of a low power-frequency sparkover voltage. This implies that the sparking gap must exhibit a very high recovery strength, this being defined as the ratio of the voltage at which the arrester just does not discharge to the peak value of the power-frequency sparkover voltage.

It is quite evident that the two requirements imposed on the spark gap, namely high recovery strength and high discharge capacity are, in principle,

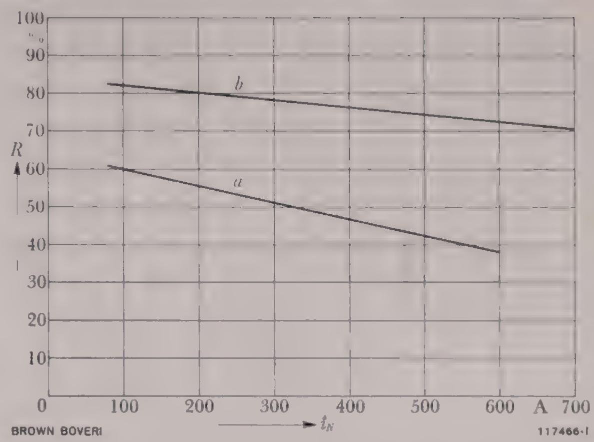


Fig. 2. – Recovery strength as a function of the follow current, measured on different kinds of arrester spark gaps

a = Plate spark gap

b = Spark gap with magnetic blow-out

R = Recovery strength, defined as the dielectric strength of the gap after the passage of the follow current, divided by the peak value of the power-frequency sparkover voltage

$\hat{i}_N$ = Peak value of the follow current

best fulfilled with a magnetic blow-out system. In this case it is less important whether the magnetic effect is produced by the inherent or an external field, than it is to ensure that the arc is not permitted to remain standing at the sparkover point, but wanders. In this way the sparkover point can be rapidly deionized and, at heavy currents, globules of molten metal are avoided.

Brown Boveri have been employing the magnetic blow-out principle for many years in their d. c. arresters, excellent results having been obtained with them in service [10]. It was therefore an obvious step to examine whether this principle could be adapted for a.c. arresters. Fig. 2 shows the recovery strength measured on two different spark gaps during development trials. The simple plate gap already exhibits a lower resistance to restriking at low current than the magnetically blown gap examined for comparison. Moreover the resistance of the former drops more rapidly with increasing current than that of the magnetically blown gap. On the other hand, the provision of magnetic blow-out naturally involves a considerably greater outlay as

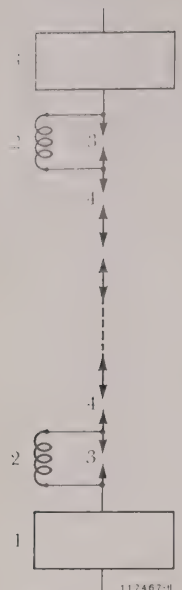


Fig. 3.– Circuit diagram showing the elements of an arrester with a magnetically blown spark gap

1 = Non-linear resistor
2 = Blow-out coil
3 = Bypass spark gap
4 = Main series spark gap

regards construction and cost. Therefore the more expensive solution will only be resorted to when the technical conditions make this necessary. The following example illustrates that by increasing the severity of the technical requirements it is possible to reach the limit of the discharge capacity of the plate gap. If, for instance, the amplitude of the follow current has to be kept at 300 A, allowing for the specified residual voltage and the rectangular impulse strength, the recovery strength of the plate gap in Fig. 2 amounts to roughly 50%. The peak value of the power-frequency sparkover voltage must then be at least $\sqrt{2}/0{\cdot}5 = 2{\cdot}8$ times the rated voltage of the arrester, and can then hardly be accommodated in the range indicated by $(\hat{u}_{a2\sim})$ in Fig. 1.

Fig. 4. – Slow-motion shots showing the passage of the surge and follow current through a magnetically blown spark gap

The shots were taken at an interval of roughly 0·23 ms.

An A.C. Arrester with Magnetically Blown Spark Gap

For high-voltage a.c. installations the Company has been supplying the type HDF lightning arrester for many years and it has rendered excellent service. However, in the meantime the technical requirements for arresters have become considerably more severe, as mentioned in the foregoing chapter, so that these arresters are not always able to comply with all the conditions laid down in the latest regulations. The decision was therefore made to develop a high-capacity arrester. The decision to change over to the principle of magnetic blow-out in the spark gap was rendered relatively easy by the fact that the Company has many years' experience with this system. Like its predecessors, the new arrester is internally subdivided into separate elements, each with a rated voltage of 9–10 kV. Following exhaustive development trials it was decided to adopt a design basically conforming to that in Fig. 3. The spark gaps 4 are situated in a magnetic field produced by the blow-out coils 2. Parallel to these is a bypass spark gap, whose duty is to carry the surge current. After discharging an overvoltage, the follow current is transferred from the bypass gap to the blow-out coils. The field produced by the coils forces the arc in the spark gaps 4 to start wandering. The gaps are so arranged that the individual arcs are simultaneously extended. The voltage drop in the arcs acts in opposition to the driving system voltage. As a result of this, the height of the stack of non-linear resistance elements can

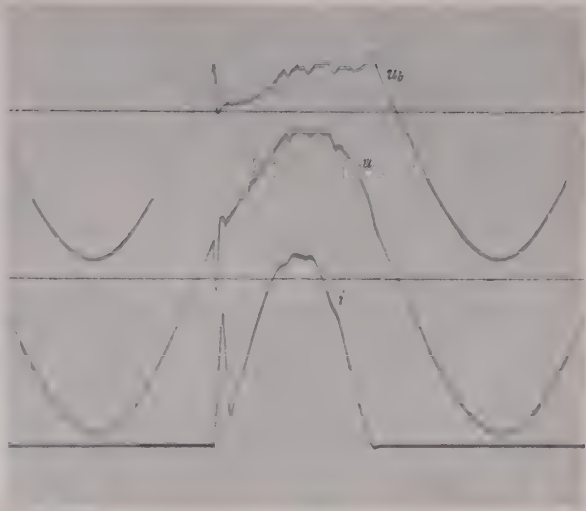


Fig. 5. – Oscillogram of the experimental operation of an arrester element arranged as in Fig. 3

The arrester is made to spark over by a current surge of 10 kA with 8/20 μs waveshape, roughly 30° after the voltage zero.

u_b = Voltage across the spark gap
u = Voltage across the arrester
i = Current through the arrester

Fig. 6. – State of a spark gap following three operating duty tests according to IEC rules

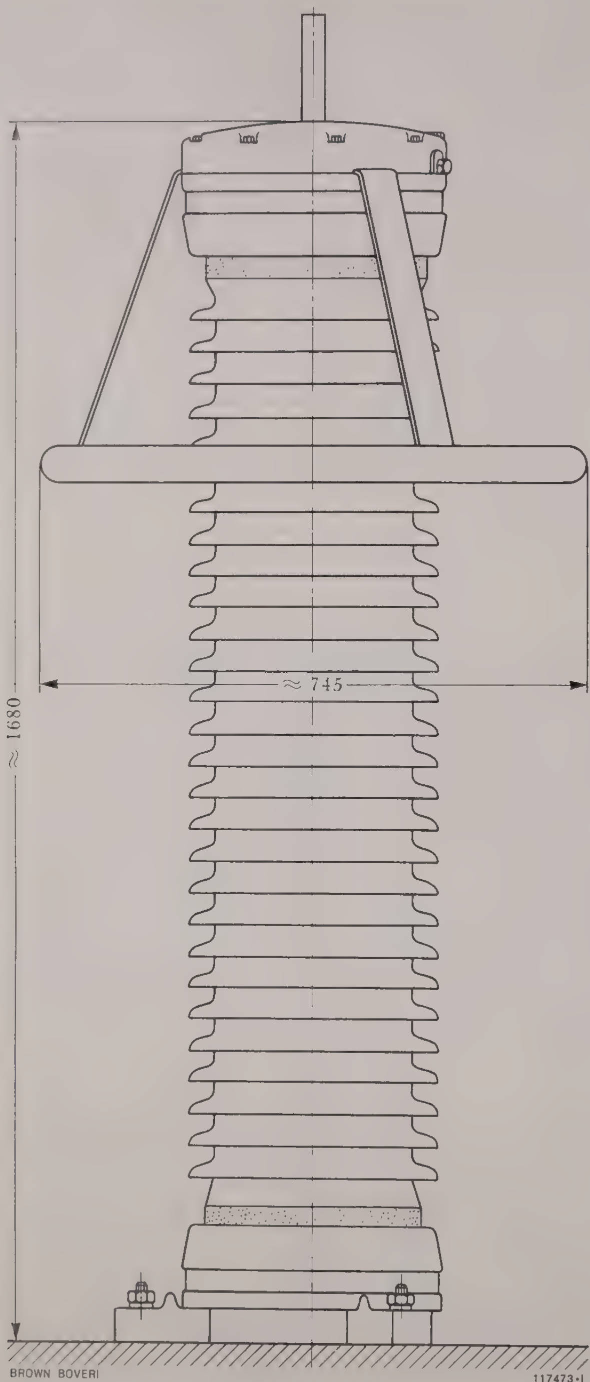


Fig. 7. – Outline sketch of the lightning arrester type HKF 130 for a maximum service voltage of 130 kV and a rated discharge current of 10 kA

Showing the approximate dimensions in mm.

be reduced for a definite permissible follow current, compared with the height of a stack in which the arc is not extended. In this way very low residual voltages are obtained. The above principle is not particularly new as it stands, but in most cases a non-linear resistance was suggested instead of the bypass spark gap 3 (cf. [1] for example). But a diverter resistance of this kind must also be dimensioned to carry the maximum current of 100 kA, like the resistors 1, besides which it results in a higher residual voltage than the arrangement described above. The manner in which the spark gaps function can be seen in Fig. 4. This shows a succession of shots from a slow-motion film taken during development trials. The shots were taken at an interval of roughly 0·23 ms. The first shot shows the arc produced by the surge current, which is rapidly extinguished. The migration of the subsequent follow current can be seen very clearly in shot 3. This follow current attains its maximum approximately in shot 15, after which the intensity of the luminous gases decreases steadily till shot 30. An oscillogram recorded during such an operation is shown in Fig. 5. Plotted therein are the voltage u across the arrester, the follow current i, and finally the arc voltage u_b across the stack of spark gaps. Ignition took place about 30° after the voltage zero, due to a current surge of equal polarity. It will be observed that the arc voltage increases almost linearly to its maximum. That is the instant at which the individual arcs have attained their maximum length. The effect of the arc extension is demonstrated in this oscillogram by the fact that the follow current attains its maximum just before the driving voltage reaches its highest value, and by the fact that the discharge is completed ($i = 0$) before the driving voltage reaches its zero.

Fig. 6 shows the condition of a single electrode following a severe discharge test. The load imposed represents about three times the load imposed during routine type tests on an arrester. As will be seen, there are hardly any sign of arcing at the sparkover point, owing to the rapid migration of the arc.

With an arrester designed according to the above principle it is possible to attain very low 100% impulse sparkover voltages and residual voltages, i.e. values 15–20% below the figures given in Fig. 1. For example, an arrester of the type illustrated in

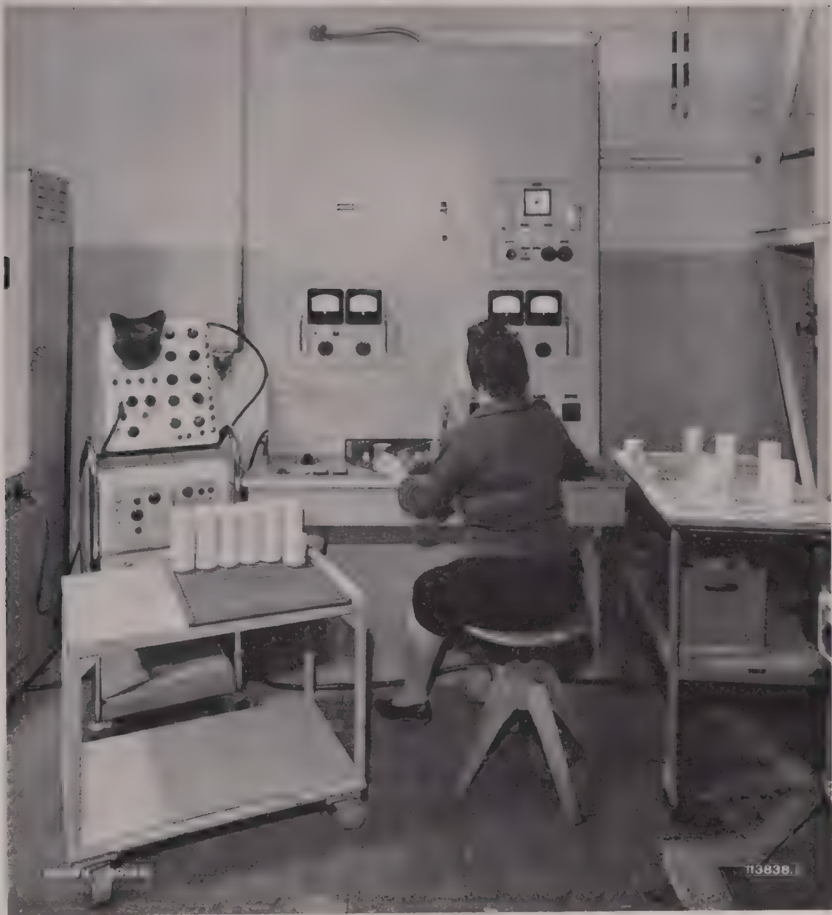


Fig. 8. – Test bench on which every resistance element for lightning arresters is tested

Following formation with several current surges each resistor is subjected to a sparkover test with a surge equal to the rated discharge current immediately followed by a half-wave impulse lasting 10 ms. The measured voltages are registered by instruments with a maximum indication.

Fig. 7 yields the following voltage and current values:

Rated voltage	130 kV (r.m.s.)
Max. value of 100% sparkover voltage	320 kV (peak)
Residual voltage at 10 kA (8/20 impulse)	340 kV (peak)
Power-frequency sparkover voltage	
Maximum	280 kV (r.m.s.)
Minimum	220 kV (r.m.s.)
Rectangular-wave impulse strength 2000 μs	500 A

Naturally the quality of a lightning arrester does not depend solely on the capacity of the spark gap, but also to a considerable extent on the non-linear resistance elements used. During the past few years appreciable improvements have been made in the quality of the resistors. A very important factor is the care with which they are tested and selected. Every resistor is, of course, formed to stabilize its properties, by being subjected to a succession of current surges corresponding to the operating duty. In addition, each resistor is subjected to a sparkover test. The testing equipment is shown in Fig. 8. Each resistor is first loaded with its rated discharge current, immediately followed by a half-wave impulse lasting 10 ms. The nominal values are recorded by instruments registering the maximum value attained, which is then stamped on the resistor. This facilitates subsequent selection and ensures that the guaranteed figures can be maintained.

The arrester described is designed on the unit construction principle, permitting a complete series to be assembled from largely identical elements.

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A NEW SINGLE-PHASE ON-LOAD TAP CHANGER FOR INCORPORATION IN LARGE TRANSFORMERS

621.316.543.3:621.314.21

The present article describes tap changers for a service voltage of 245 kV, which were employed for the first time in 400-MVA transformers for the Sils (Domleschg) power station of the Kraftwerke Hinterrhein AG., and in 600-MVA transformers in the Breite substation of the North-East Switzerland Power Co. Reference is made to the various problems which had to be solved during development, the special features of the design and the important question of reliability, with a brief mention of the results of tests.

ECONOMIC considerations lead to the employment of increasingly large transformer units in power transmission systems. The highest ratings so far attained by this Company are 542 MVA for a three-phase unit [1] and 1100 MVA for a bank of three single-phase units [2], both figures being the rated throughput. Likewise, owing to the need to achieve maximum possible economy in operation and to make the best use of the capacity of the available equipment, an increasing number of large transformers are being equipped with tap changers to regulate the transformation ratio on-load. The same severe stipulations regarding reliability which have to be fulfilled by such transformers of extremely high capacity, also apply to the tap changers incorporated in them, because failure of the tap changer often has the same result as a defect in the transformer itself, and leads to very expensive interruptions of the service.

A tap changer is a complex piece of apparatus and, compared with the transformer, contains numerous parts exposed to wear, as well as contacts which have to interrupt switching arcs. It is therefore much more difficult, but no less essential, to achieve a high degree of reliability in tap changers. This requirement will always be the guiding factor for the designer. Everything else is of secondary importance. It goes without saying that this was also the case in the development of the new Brown Boveri tap changer.

Design of the Tap Changer

The single-phase on-load tap changers described in this article are mainly intended for the very high transformer capacities. They are designed for a service voltage of 245 kV and, when rated 1000 A, can regulate a capacity of 400 MVA; the 2000-A model can handle 800 MVA.

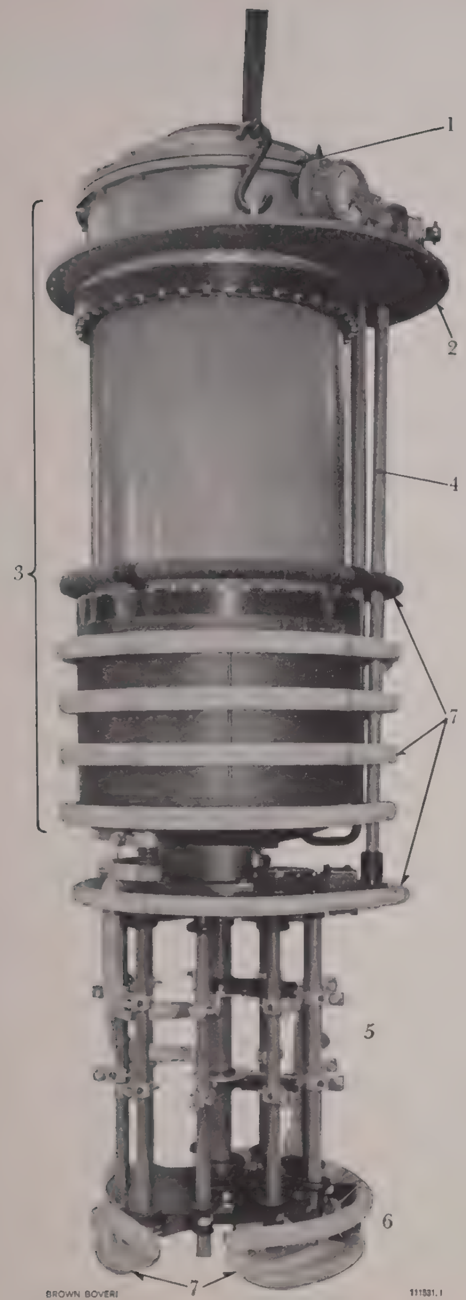


Fig. 1. – Single-phase on-load tap changer type LB 245

Max. service voltage	245 kV
Rated current	1000 A
Number of tappings	± 17 (total 34)
Max. tapping voltage	$5/\sqrt{3}$ kV

1 = Cover of diverter switch container
2 = Tap changer head with fixing flange
3 = Diverter switch container with insulation. The retractable diverter switch is in the lower part
4 = Actuating shaft
5 = Selector with two contact tracks
6 = Plus-minus changeover switch or coarse selector
7 = Electrodes screening live parts

When constructed as a built-in unit, certain requirements regarding the height are easier to fulfil, which is particularly important for transformers to be installed in underground caverns, or for mobile transformers. It also proves advantageous if the controlled voltage has to be led away through a cable.

With 17 tappings and a maximum tap voltage of $5/\sqrt{3}$ kV the changer has a maximum range of variation of $\pm$ 17·5 %; when equipped with an additional coarse selector or a plus-minus changeover switch with 34 stages, its range is extended to $\pm$ 35 %, referred to 245 kV.

The electric strength of the selector and diverter switch to earth is tested at 460 kV on 50 c/s, and at 1050 kV with a 1/50 impulse. The dielectric strength between individual parts of the changer, connected to the various tappings of the winding are designed to cater for the non-uniform distribution of the impulse voltage across the windings. The short-circuit strength is also sufficiently high to meet all requirements in this respect. In the 1000-A type it is $1{\cdot}8\sqrt{2}\times 16$ kA, while for the 2000-A type it is $1{\cdot}8\sqrt{2}\times 30$ kA.

Layout and Principle of the Selector and Diverter Switch

Like all tap changers for high capacities, the one dealt with in this article comprises the main elements: selector, diverter switch and motor-driven operating mechanism. As Fig. 1 shows, the selector is immersed in the transformer oil, while a separate enclosure is recessed in the transformer tank to accommodate the diverter switch. The latter is designed as a plug-in unit and, when the cover of its enclosure is removed, can be easily withdrawn for replacement of the switch contacts. Since the tap changer is operated from below through a socket-type coupling, and the electrical connections are also made through pins and sockets, it is a very simple matter to extract the diverter switch. Owing to the remarkably rigid design, the head of the tap changer, the diverter switch enclosure and the selector form a complete assembly which is lowered into the transformer tank and merely fastened down at the upper flange. There

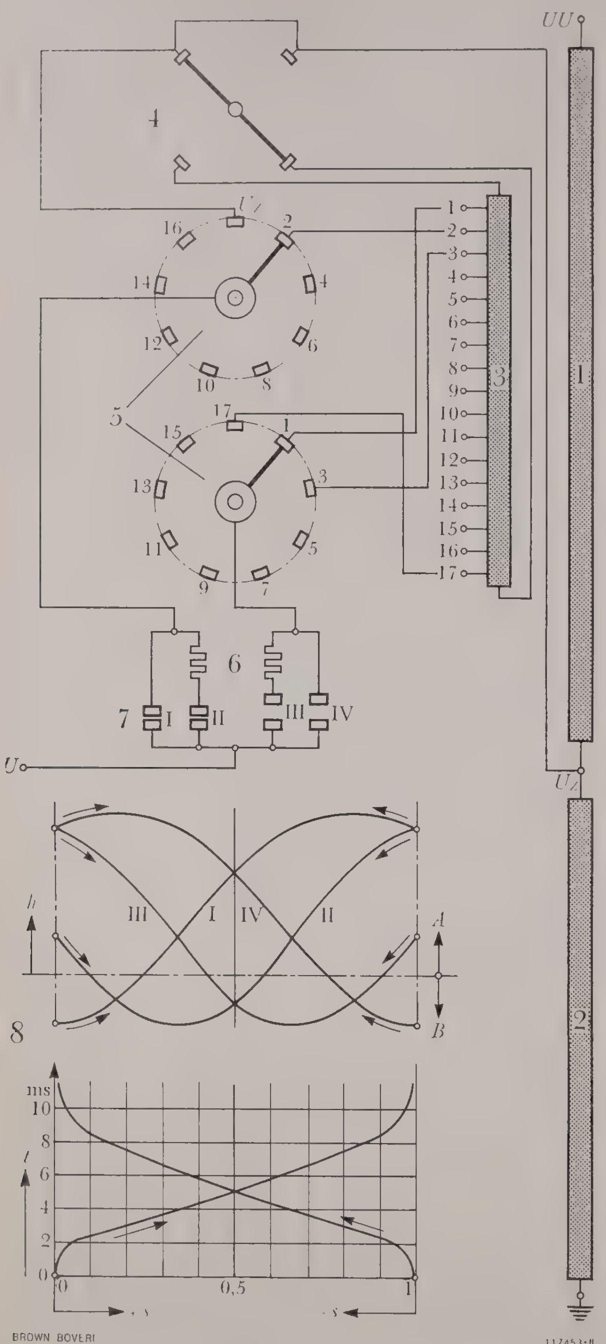


Fig. 2. – Circuit diagram of a transformer pole with tap changer, and the movement curves of the diverter switch contacts

U = Input terminal
1 = Series winding ($UU - U_z$)
2 = Parallel winding (U_z–neutral)
3 = Regulating winding
4 = Plus-minus changeover switch
5 = Tap changer
6 = Diverter resistors
7 = Diverter switch contacts (I, II, III, IV)
8 = Diagram showing movement of the diverter switch contacts (contact travel h) in terms of the motion of the spring mechanism (distance $\pm s$) and time t
A = Contacts open
B = Contacts closed

is no need for any support from below. Thus the lower insulation is immersed in free oil, enabling the overall height to be reduced without additional insulation being necessary.

In order to keep the oil in the diverter switch container in good condition, bearing in mind that it has to withstand the full service voltage to earth, a filter set can be inserted to clean the oil by circulation. The oil is drawn off at the bottom of the container and, after being cleaned, pumped back in at the top.

The selector, as shown in Fig. 2, has two contact tracks, one for the odd-numbered tappings, the other for the even-numbered, each having its own contact arm. The two arms never move at the same time; while the stationary arm is carrying the current, the other can move on to the next position desired.

The diverter switch always makes contact with the correct arm of the selector. In doing so the current must not be interrupted, yet it must not be possible for the two tappings concerned to be short-circuited. This is taken care of by a set of four changeover contacts and two diverter resistors. Fig. 2, apart from showing the circuitry of the tap changer, also indicates the curves of the motion of these contacts. Since they are actuated through cranks, the curves are sinusoidal, the mutual phase displacement being such that the desired switching sequence is obtained.

Interesting Details

From the multitude of problems encountered during the development of a tap changer, a few will be picked out and dealt with in greater detail.

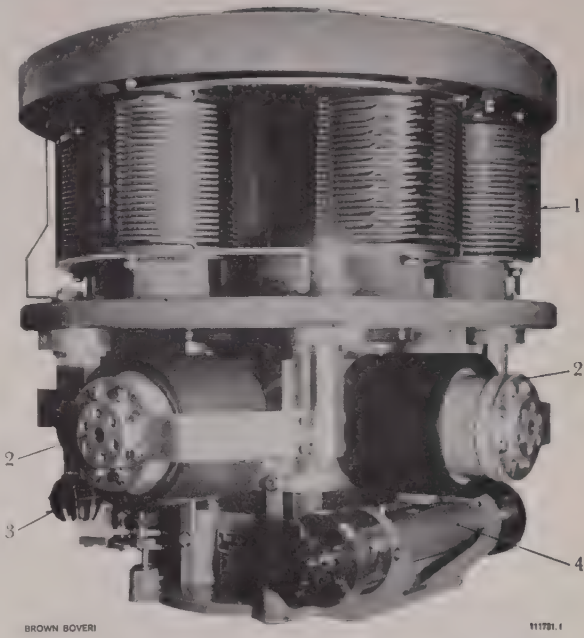
Spring Mechanism of the Diverter Switch

The spring mechanism driving the diverter switch is fitted in the retractable section. During the relatively slow motion of the selector it is loaded, then released to switch over the load instantly in about 0·1 s.

Fig. 3. – Diverter switch of the on-load tap changer

This part is designed as a plug-in assembly and can be easily removed from its container when the contacts have to be changed.

1 = Diverter resistors
2 = Arcing chambers
3 = Plug sockets
4 = Hydraulic damper



As soon as mention is made of a spring mechanism, doubts tend to arise regarding the reliability. It is indeed common knowledge that such spring operators are often the cause of trouble in a wide variety of switchgear units. Nevertheless it must be possible to design this element in such a way that its functional reliability is in no way inferior to that of the remaining parts. A prerequisite for this is the suitable fundamental conception, which yields the stipulated movements in the simplest possible manner. The extremely robust design of the spring mechanism of the diverter switch can be seen from Fig. 5.

It operates very smoothly with hardly any wear. The operation is very simple, three rollers running up one side of the cylinder flank to load the springs, which are released simply by rolling over the highest point of the curve. Thus no latching action is needed. In order that there may be no impact, leading to undue wear or stresses, the moving masses are retarded at the end of their movement by hydraulic dampers (Fig. 3). The actual motion of the spring mechanism with respect to time is shown in Fig. 2.

Arc Chambers of the Diverter Switch

The contacts of the diverter switch must be capable of interrupting quite appreciable loads. On account of the motion of the spring mechanism, there is only a very limited time available for extinction of the arc. The full quenching action must therefore take effect only a few milliseconds after the contacts part. The arrangement must also be able to perform the large number of operations which take place until the diverter switch has to be overhauled again. It was soon discovered that this condition is difficult to fulfil with the necessary dependability by open contacts immer-

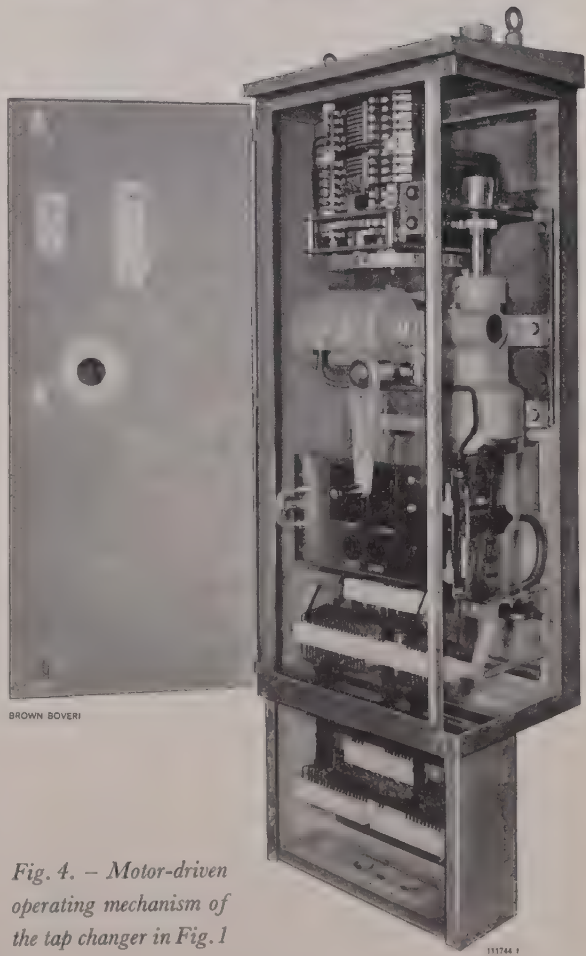


Fig. 4. – Motor-driven operating mechanism of the tap changer in Fig. 1

Access to all components is afforded by the door and detachable side panels. In addition to the normal remote control, it can also be controlled locally with manual or motor operation.

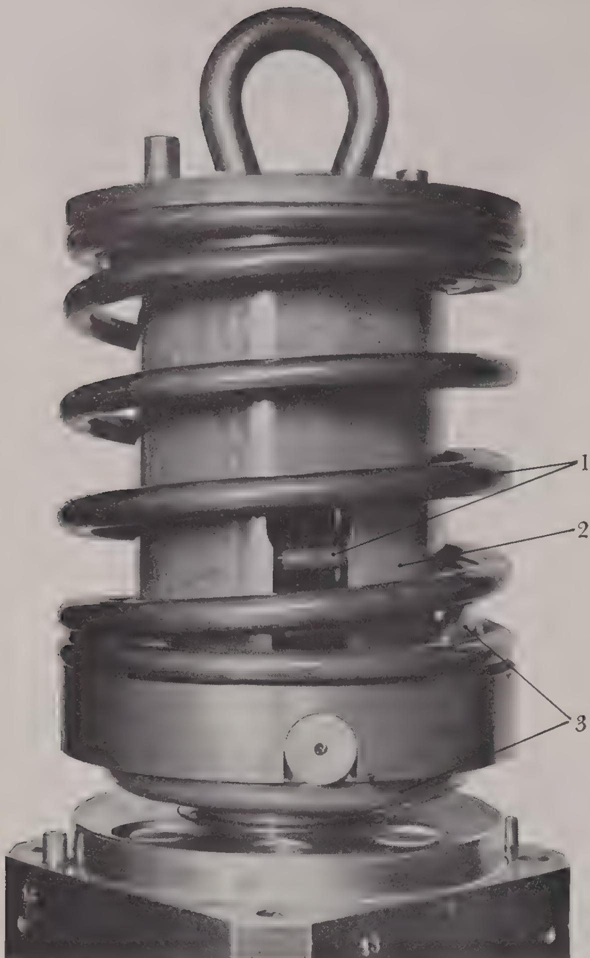


Fig. 5. – Spring mechanism of the diverter switch

Some of the external parts have been omitted to give a better view of the important elements.

1 = Operating springs
2 = Driving cylinder (hollow) for the slow loading motion
3 = Cam cylinder producing the spring action operating the diverter switch contacts

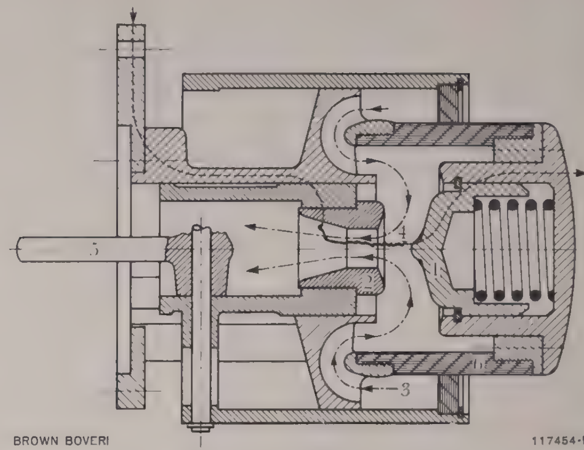


Fig. 6. – Principle of the arcing chamber of the tap changer

1 = Sprung fixed contact
2 = Driven contact, designed as nozzle
3 = Pump and movement of quenching medium when contact open (broken line)
4 = Switching arc and current path (dotted)
5 = Driving crank
6 = Insulating cylinder

sed in oil. Convector chambers are not suitable either because the flow action which quenches the arc is produced by the arc itself. The arcing time depends on the current and is too long, particularly with low currents.

The development finally led to an arc extinction chamber with forced flow, the principle of which is illustrated in Fig. 6. The extinction medium is automatically forced into the arc zone, simultaneous with the opening of the contacts, and surrounds the arc as it flows out through the nozzle. Thus the arc only comes into contact with the extinction medium and the non-eroding material of the contacts. With this chamber very short arcing times can be attained. Over the full range of the necessary switching capacity the arc is extinguished at the first current zero. The number of operations which can be performed before an inspection is required is very high and only limited by the life of the replaceable contacts.

Insulating Material

Paper-based laminates bonded with phenolic resin, which have often been used for insulating parts, such as supports, shafts or cylinders have, by and large, excellent electrical and mechanical properties when immersed in dry oil. However, the dielectric strength is very dependent on the presence of moisture, which the laminate absorbs from the atmosphere. Thus, though by no means desirable, either the oil has to be dried or the laminate specially impregnated shortly before erection, or allowance must be made for these parts during the treatment of the transformer, because the material becomes brittle at elevated temperatures and consequently its mechanical strength diminishes.

In the search for a new insulating material a whole range of possible materials was examined and exhaustive tests carried out. Some of these tests lasted over a year, in order to determine the durability under arduous conditions. The material finally chosen was a synthetic resin reinforced with gas fibres which, in addition to an excellent performance, possesses the following properties:

- High dielectric strength, which in good-quality oil is somewhat better than paper-based laminates.
- High dielectric strength in damp or dirty oil.
- Very high mechanical strength.
- Sufficient mechanical creep strength in oil at the normal operating temperature of 90 °C.
- Low moisture absorption.
- The new material does not need to be specially dried and can withstand the normal process of drying the transformer without being affected in any way.

Mechanical Life and Reliability

Like all switchgear, a tap changer must exhibit a useful life consistent with the manner of its operation. In power supply networks it may be assumed that at the most 10000 operations will have to be performed annually, giving a total of 250000 operations in 25 years. Having regard to other applications, for which a much higher number of operations is stipulated, the new tap changer is designed to have a useful life of several million operations. This number applies equally to the selector and diverter switch, as well as to the motor-driven operating mechanism. Exceptions are a small number of parts exposed to particular wear, such as the diverter switch contacts, which have to be renewed at definite intervals.

The statement of the useful life alone does not give any indication of the reliability, which is essential if the true performance is to be assessed. A figure by which this may be judged is the average number of years service a tap changer or the associated transformer gives before a breakdown occurs in it. Naturally a high standard of reliability is not only necessary in a tap changer, particularly in the selector and load switch, but also essential, because the least trouble in these components can lead to very serious breakdowns and even damage in the transformer.

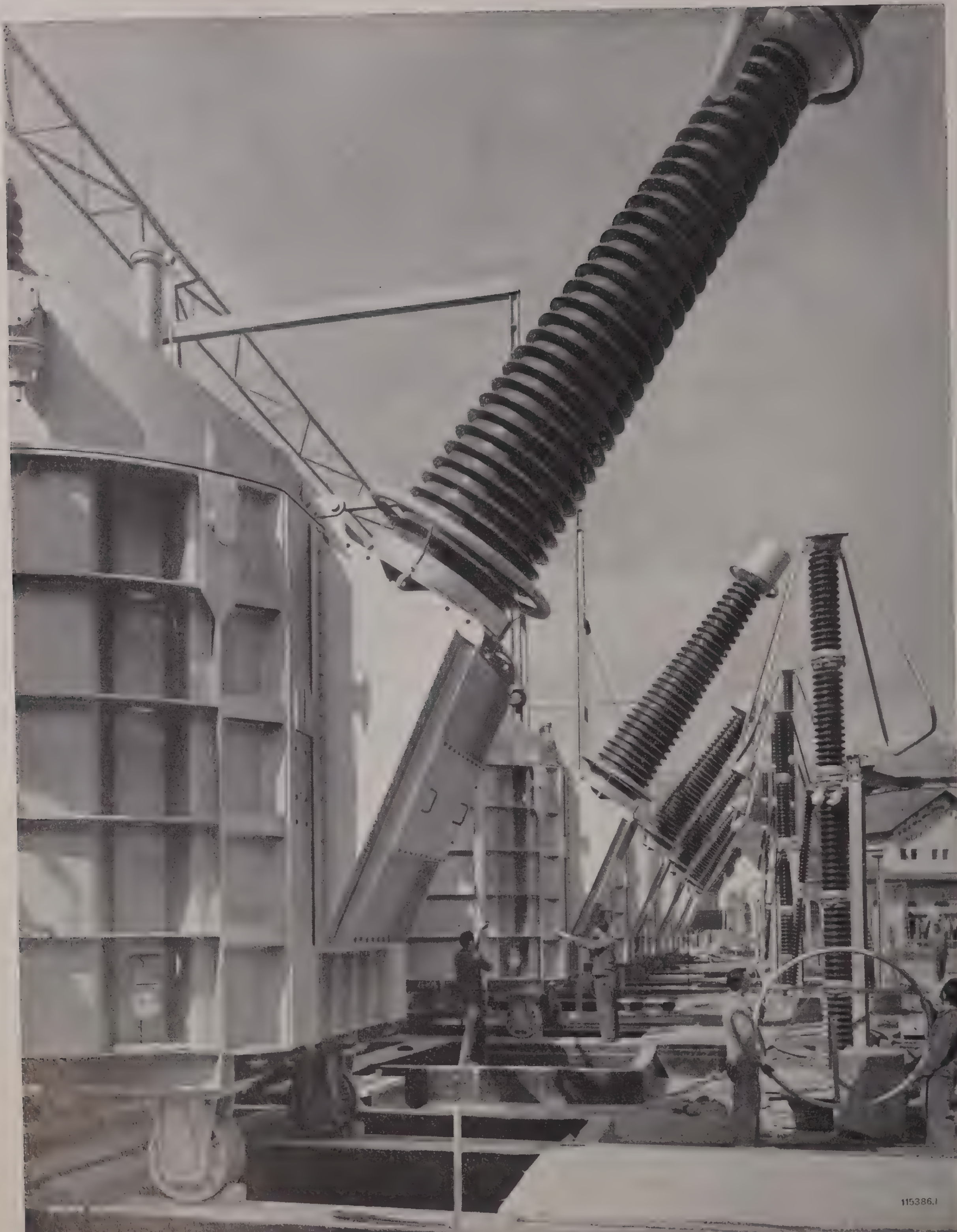
To gain some idea of the standard of reliability achieved in the past, a glance may be cast at the breakdown statistics of a large power supply undertaking [3], covering a period of 20 years. According to this report, the selectors and diverter switches of unspecified make in a total of 2965 unit-years of service gave rise to 18 stoppages, which works out at 1 breakdown in 165 unit-years.

This result, however, appears most unsatisfactory when compared with the figures attained hitherto by the Brown Boveri external type of tap changer. According to the available figures, which cover a period of roughly thirty years and more than 20000 unit-years of service, the reliability was more than five times as good as the above result.

When designing the new 245-kV tap changer every effort was made to attain still better reliability figures. Such extreme stipulations can only be made, though, when development work is backed by nearly half a century of experience. Moreover, it is inevitable to aim at the specified reliability with all severity in the design stage. There is practically no other method of attaining this goal. Even endurance tests cannot render any more assistance because the probability of a breakdown occurring is far too small. Only when large numbers are in service can the proof be obtained of whether the anticipated reliability is really there. Consequently everything must be done during the development period to ensure that the tap changer passes this test of its capability.

Test Results

Although the final decision regarding the quality of an item of equipment can only be reached after many years service, conscientiously performed trials can provide a useful provisional result with regard to most matters. The mechanical endurance test, for instance, is one way of recognizing any serious short-



A row of 400-kV transformers at Sils power station, Grisons, Switzerland

The single-phase on-load tap changer described in the accompanying article is enclosed in the regulating transformers, not visible in the above picture, which are connected to the main transformers to form an integral unit

comings and design weaknesses in good time. The new tap changer was made to perform over a million operations at normal service conditions in about one year; it succeeded in passing this test without any mechanical defects or serious wear occurring.

A factor of great importance in service is the life of the contacts of the diverter switch, because their replacement involves a short interruption of the service. During the tests which were carried out it was established that, under very severe operating conditions, e.g. like those experienced at Sils power station, the useful life of the contacts would be at least 50 000 operations. It may therefore be expected that the contacts will not have to be renewed until the transformers have been in service for over five years, which may be regarded as a very satisfactory result.

The capacity of the arcing chambers was investigated in series of exhaustive tests, during which every imaginable load condition likely to occur in service was taken into consideration. It was established that the arcing chambers possess a very high switching capacity and are quite capable of performing their duties, with plenty to spare. Even when subjected to overloads equal to many times the rated current, they are still able to assure perfect transfer of the load.

To judge by the good results obtained from all the tests performed, the new tap changer may be regarded as at least equal to the best of the well-known units of this kind. It may therefore be expected to live up to these expectations in service.

(KME) K. BÜHLER

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RECENT BROWN BOVERI CONTRIBUTIONS TO THE DEVELOPMENT OF ELECTRIC TRACTION IN FRANCE

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Simplicity, minimum weight and optimum tractive effort are the main aims of designers of modern traction vehicles. Referring to examples of a motor-coach and locomotive design, the author describes the present state of development in France. Brown Boveri's contribution includes a number of newly created designs in the sphere of electric motors and electrical control gear. A high-output self-ventilated, traction motor, consuming pulsating current, deserves special mention, as well as the new, compact, lightweight starting resistors for d.c. vehicles, and a modern tap changer used for controlling such vehicles.

THE FRENCH National Railways, Société Nationale des Chemins de Fer Français (SNCF), have added some remarkable new models to their stock of traction vehicles. With an open mind for progress, original ideas have been snapped up, put into effect and tried out. The electric traction equipment of the SNCF is rightly admired, even outside the narrow specialist circles, and has received due recognition [1].

Brown Boveri's associate company in France, the Compagnie de Construction de Gros Matériel Electro-Mécanique, is playing a major part in the design and construction of French traction vehicles. From this activity admirable opportunities arise for applying well-known and tried Brown Boveri traction products, and for putting new ideas and developments into practice. The summary which follows will refer to two modern types of traction vehicle, drawing particular attention to some of the notable features of the equipment supplied by this Company.

A. Three-Coach Compositions with Single-Motor Bogies for Suburban Traffic to the North and East of Paris

Factors Governing the Choice of Type

Credit is due to the SNCF for their recognition of the excellent adhesion of single-motor bogies and for developing them energetically. After the first bogies of this kind had been tried out in the Swiss-built two-frequency rectifier locomotives No. 20103/4 [2], and subsequently, when employed in locomotives of French manufacture, completely fulfilled the expectations and exhibited excellent traction qualities, it was an obvious step to apply the same principle to motor-coaches.

Modern suburban traffic demands a high tractive effort on starting and rapid acceleration. With a reduced number of axles this can be achieved all the better when the most is made of the friction between the wheels and the rails. The single-motor bogie, on which the tractive effort is applied at a very low point, and with the driving axles mechanically coupled through the gearing, largely meets this stipulation. The ability to concentrate the traction equipment on a single bogie leads to an extremely simple arrangement of the electrical installation. The reversing switch, isolating contactors, metering and monitoring equipment, cable and other installation material require a minimum of attention and maintenance.

It was considerations of this nature which induced the SNCF, towards the end of 1958, to place on order four three-coach compositions consisting of a motor-coach, a driver-trailer and an intermediate trailer coach, a view of which can be seen in Fig. 1. Approximately two years later they commenced regular service early in 1961.

General Data, Main Circuit Equipment

In conformity with their duties in the northern suburbs of Paris, the trains are designed to run off a supply of 25 kV at a frequency of 50 c/s. Three of the units are equipped with semiconductor rectifiers and pulsating-current motors. The fourth train has

Fig. 1. – Three-coach composition of the Société Nationale des Chemins de Fer Français (SNCF), serving suburban routes north and east of Paris, running off 25 kV, 50 c/s

The two axles of the inner bogie of the motor-coach are jointly driven by a single pulsating-current motor with a one-hour rating of 750 kW.

single-phase commutator motors and – as another special feature – an infinitely variable regulating transformer.

Brown Boveri are well represented in these trains, for which they supplied some important components. Produced in the works of the Compagnie Electro-Mécanique (CEM) in Paris were the pulsating-current motors, the airblast circuit-breakers and the low-voltage tap changers for all the rectifier trains. For the fourth train the airblast circuit-breaker and the regulating transformer were provided.

Fig. 2 is a sketch showing the outline and principal dimensions of these trains. From the traction point of view, the following figures are of interest:

Continuous operation:

Power at wheel tread	613 kW at 47·3 km/h
Tractive effort at wheel tread	4750 kg

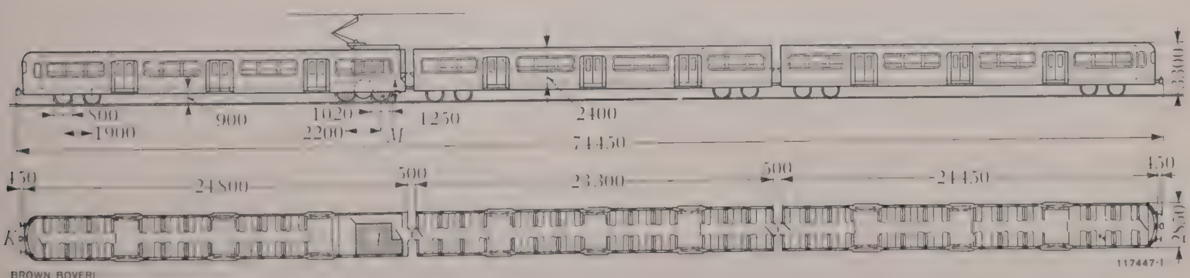

Fig. 2. – Outline sketch of the compositions operating on the SNCF lines in the north and east of Paris

The electric traction equipment is accommodated in a compartment immediately above the driving bogie, thus keeping the wiring extremely short and simple. (Total weight 110 t; adhesion weight 34·7 t.)

M = Motor bogie K = Automatic coupling A = Control gear compartment

From left to right: motor-coach, trailer coach, driver-trailer coach.

Seating accommodation: 48 1st class, 230 2nd class Standing accommodation: 8 1st class, 112 2nd class

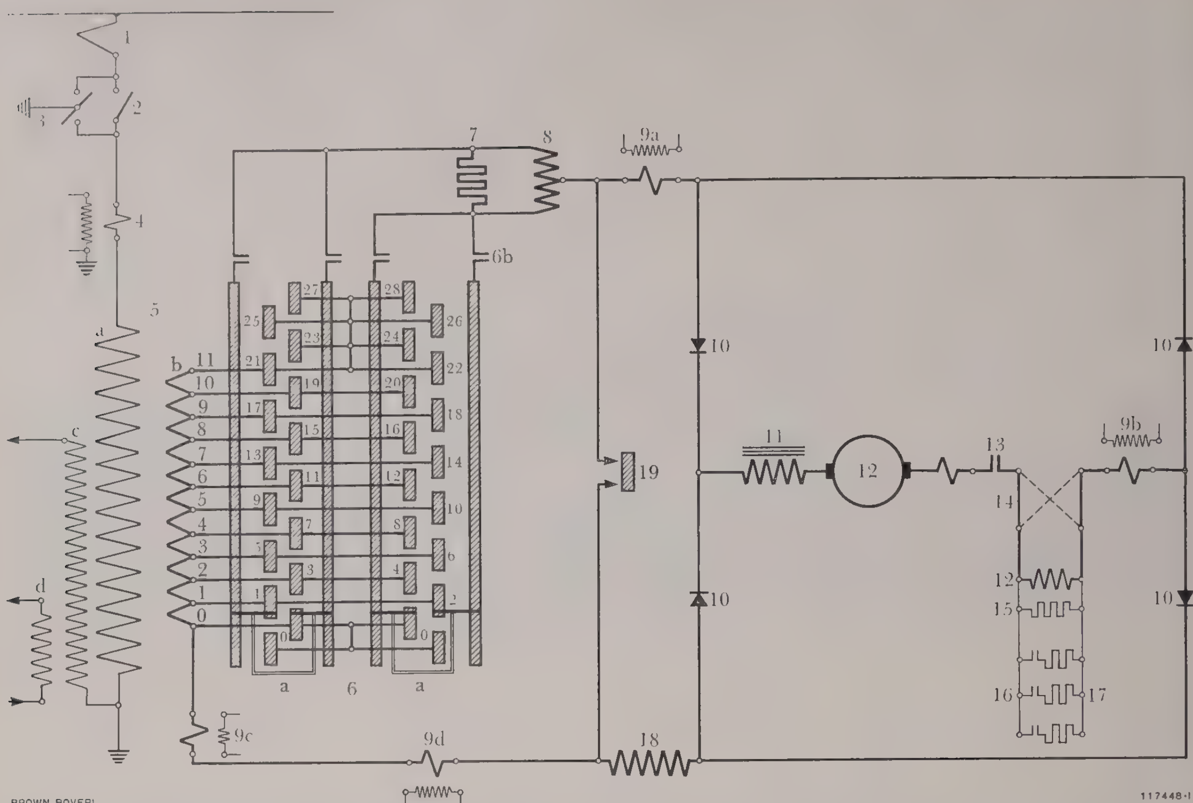

Fig. 3. – Schematic diagram showing the arrangement of the main circuit in the three motor-coaches of SNCF equipped with silicon rectifiers

1 = Current collector
2 = Main circuit-breaker
3 = Earthing switch
4 = Primary current transformer
5 = Power transformer
5a = Primary winding
5b = Secondary winding
6 = Tap changer
6a = Selector contact
6b = Diverter switch
7 = Diverter resistor
8 = Voltage divider coil
9a = Current transformer tripping shorting switch
9b = Current transformer tripping shorting switch
9c = d*i*/d*t* transformer tripping shorting switch
9d = Current transformer monitoring starting current
10 = Rectifier
11 = Smoothing choke
12 = Traction motor
13 = Isolating contactor
14 = Reversing switch
15 = Resistance parallel to motor field
16 = Field-weakening contactor
17 = Field-weakening resistors
18 = Reactor
19 = Shorting switch protecting rectifier

One-hour operation:

Power at wheel tread	730 kW at 45 km/h
Tractive effort at wheel tread	5950 kg
Tractive effort on starting:	7700 kg
Top speed:	120 km/h

The principle of the main circuit of one of the rectifier trains is illustrated schematically in Fig. 3. The current collector and airblast circuit-breaker are those standardized by SNCF. The main transformer, designed for a total power of 800 kVA, is situated in the equipment compartment immediately above the driving bogie, which also contains most other items of electrical equipment. The heated transformer oil flows through a naturally ventilated cooling system mounted at the end of the motor-coach adjoining the trailer coach. A total of twelve tappings are brought out from the secondary winding of the transformer and connected to the tap changer.

The tap changer, consisting of the selector operating off-load and the cam-actuated diverter switch, is the Brown Boveri low-voltage tap changer described in an earlier publication [3]. It is operated in the present case by an electric servomotor, a method which is

standard practice with SNCF. By means of the single-reactor voltage-divider arrangement it is possible to obtain 22 motoring stages in the range from 36 to 1150 V. Overvoltage protection on the secondary side is afforded by combinations of capacitors and resistors connected between the ends of the windings and earth.

The traction current is rectified by silicon diodes of three different kinds. In two of these installations they are artificially cooled, in the third they are naturally ventilated. Throughout, the three-phase bridge is employed, the limbs of the bridges consisting of various combinations of parallel and series elements. Defects in the cells are indicated by lamps of the annunciator lighting up. In the event of a short circuit an electronically controlled shorting switch comes into action, which trips the main breaker of the locomotive through an auxiliary contact.

Owing to the different makes of diodes being different in size, number and in their method of cooling, it is natural for the weights of the three sets of rectifier equipment to vary appreciably from one another. For smoothing the current an oil-cooled reactor is incorporated, but the pulsation of the current at about 30 % of the one-hour load is still quite considerable.

Traction Motor and Axle Drives

The traction motor is designed with six poles as a compensated series-wound motor for the following data:

Rated voltage:	850 V
Continuous output:	630 kW at 800 A speed 775 rev/min
One-hour output:	750 kW at 950 A speed 740 rev/min

Originally the motor was designed for ventilation by a separately driven fan. But to simplify the auxiliaries, preference was later given to the self-ventilated design although it is unusual for traction motors of this size and rating. At the same time the voltage and current were modified to suit the rectifier installation. It is worth mentioning that, as a result, while the continuous output of the motor was slightly reduced, the weight increased by 21 % and the diameter of the frame by 6 %. But of course, with this arrangement, the fan and its motor, with the associated control gear and wiring were dispensed with.

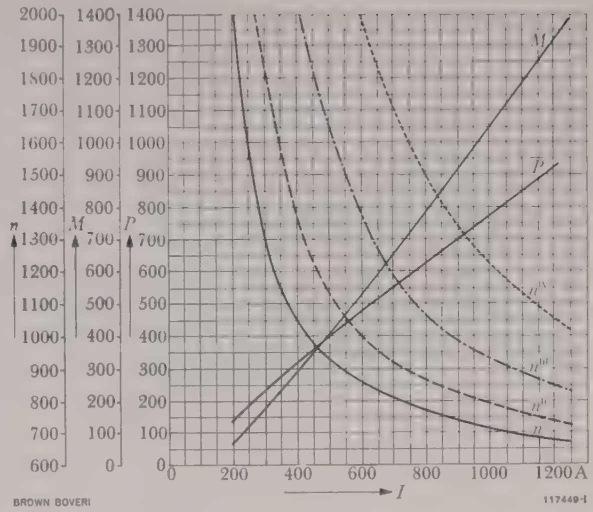

Fig. 4. – Characteristics of the pulsating-current motor employed on the single-motor bogies of the rectifier motor coaches on the SNCF lines serving the Paris suburbs

Terminal voltage 850 V
One-hour rating 750 kW at 740 rev/min and 950 A
Continuous rating 630 kW at 775 rev/min and 800 A

P = Power output (kW)
M = Torque (kgm)
n = Speed (rev/min)
I = Motor current (A)

n^{I} ——— with permanent field-weakening $I_F = 0{\cdot}8\ I$
n^{II} – – – – – with additional field-weakening $I_F = 0{\cdot}58\ I$
n^{III} –·–·–·– with additional field-weakening $I_F = 0{\cdot}4\ I$
n^{IV} -------- with additional field-weakening $I_F = 0{\cdot}28\ I$

The magnetic circuit is designed in accordance with the tried Brown Boveri principle of the pulsating-current motor [4]. Whereas the main magnetic flux primarily flows through the solid cast-steel frame, the interpole flux can follow a completely laminated path, enabling it to respond to changes in the main current almost undamped. Permanently connected in parallel with the main pole winding is a resistance which carries about 20 % of the motor current. For control purposes the field current can also be reduced to 58, 40 and 28 % of its full value. Fig. 4 shows the most important characteristics of the motor.

The rotor slots contain a four-layer Latour winding, which is ideal for pulsating-current motors on account of its good commutation properties. Its rather wide zone of current change-over has hardly

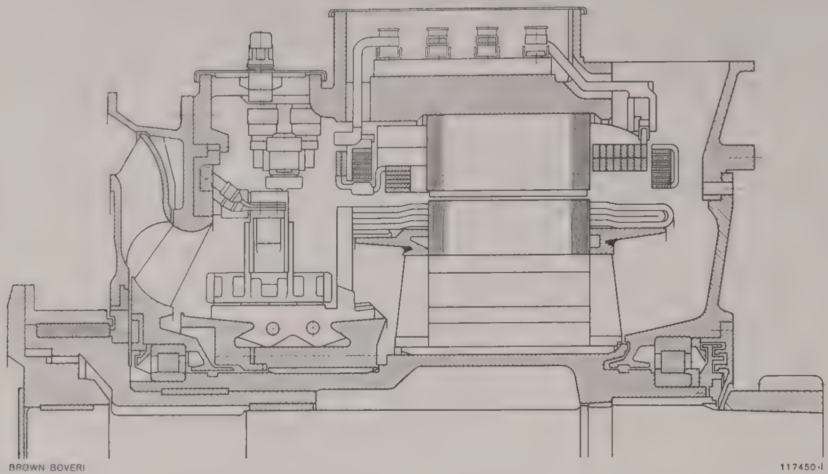

Fig. 5. – Sectional elevation of the pulsating-current traction motor

A powerful fan mounted outside the end-shield at the commutator end draws the cooling air through the passages in the stator and rotor. The torque is transmitted to the gear pinion by a quill shaft inserted in the hollow shaft of the rotor. The coupling between the two shafts is made flexible by the incorporation of rubber elements.

any adverse effect owing to the large pole pitch of such machines.

The windings are wrapped and impregnated with insulation of class F. Connection between the rotor conductors and the commutator is afforded by vanes. The intense forced draught of air cooling the rotor striking these vanes greatly helps to dissipate the heat generated. In spite of the fact that full advantage is taken of the thermal capacity of the rotor winding, the temperature of the commutator is surprisingly low.

The rotor body and the commutator are mounted on a hollow shaft rotating in greased cylindrical roller bearings. Inserted concentrically in the hollow shaft is a quill shaft, the commutator end of which is in a flexible mounting employing rubber elements (Fig. 5). The other end of the quill carries the overhung pinion which engages in the intermediate wheels of the gearing. The large gear-wheels are also mounted in a rigid gear-box. They surround the driving axles, the power being transmitted by a Cardan shaft of the well-known Jacquemin-SNCF design. A notable feature of this transmission system is the arrangement of the flexible members before the pinion, thus permitting the coupling between the bogie axles through the Cardan shaft and gearing to remain rigid. From experience this arrangement has a beneficial influence on the starting performance of single-motor bogies. Fig. 6 depicts the bogie, complete with motor, ready for assembly with the coach.

The type tests on the pulsating-current motor were carried out at the Vitry research laboratories of the

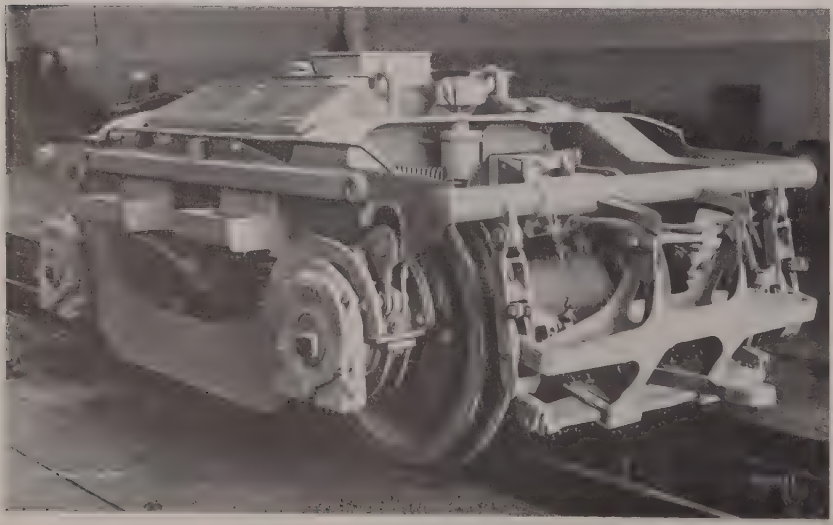

Fig. 6. – Single-motor bogie complete with motor and gearing, ready for assembly with the body of the motor-coach

The bogie and axle drive are of the design widely employed in France, known as Jacquemin-SNCF. They were manufactured in the Usines Schneider, Le Creusot.

Fig. 7. – B'B' locomotive No. 9401 of the SNCF in service

This lightweight French locomotive for 1500 V d.c. is used for hauling moderately heavy passenger and goods trains. Though weighing only 60 t it develops a continuous output of 2130 kW and is capable of speeds up to 130 km/h.

SNCF. The test sequence based on IEC recommendations was augmented by a number of special tests, including a heat run for one hour at 1000 V and 950 A, during which the permitted temperature rise was not exceeded, although the output was almost 900 kW. Another interesting factor was the behaviour with currents with up to 40% more than the normal pulsation. In the course of further tests the supply voltage was raised to 2000 V at full speed, without flashover occurring on the commutator, or any other kind of disturbance. These excellent results obtained on the test-bed have since been completely confirmed in practice.

Control and Auxiliaries

The remote control of the tap changer mechanism from the driver's cabs employs the impulse principle. The controller provides facilities for actuating the tap changer either step by step or continuously. In the latter case the process of stepping up is supervised by a relay carrying the traction current, the threshold value to which it responds being variable in three stages on the controller. Wheel slip is detected by a tachometric device, signalled visually and counteracted automatically by giving a command to the tap changer, reversing its direction.

If desired, a number of compositions can be controlled by multiple control from a single cab.

In accordance with the aim of greater simplicity, the 220-V auxiliaries are also restricted to the absolutely essential. The compressor motor is fed with pulsating current from an auxiliary silicon rectifier, while the oil pump of the transformer and the rectifier fan are driven by single-phase induction motors with a capacitive auxiliary phase. For charging the battery, consisting of 48 cadmium-nickel cells, there is a charging set composed of a transformer, regulating choke and selenium rectifiers. The heating circuits are supplied from a special winding of the main transformer, at a voltage of 1500 V. The fluorescent interior lighting of the train is connected to the auxiliary mains of the train. Should the supply from contact wire fail, the emergency lighting supplied from the battery is automatically switched on.

D.C. Locomotives of the SNCF Series B'B'9400

General Features

In the new d.c. locomotives of the 9400 series, with the axle sequence B'B' and equipped with single-motor bogies, the SNCF now possess a powerful, lightweight traction vehicle [5] for moderately heavy passenger and goods traffic on their lines supplied at 1500 V d.c. Weighing only 60 t in working order, the locomotive has traction motors which develop a continuous output of 2130 kW at 50 km/h, corresponding to a tractive effort at the wheel tread of 15·2 t. Even at the top speed of 130 km/h a tractive effort of 5 t is still exerted. Fig. 7 shows the vehicle in service, while Fig. 8 is a simple outline sketch.

The development and construction of a locomotive for the above output and speed rely on close collaboration between the designers of the mechanical part and the suppliers of the motors and control gear,

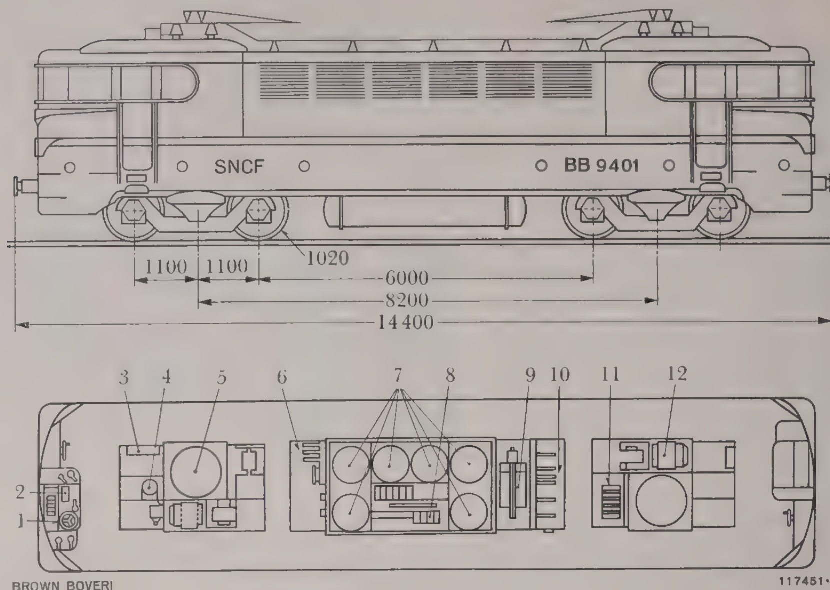

Fig. 8. – Outline diagram of the B'B' locomotives series 9400 of the SNCF

The single-motor bogie with short wheel-base and low point of application of the driving power is also provided on these vehicles and, in conjunction with various other new items, lends it excellent starting and running properties.

1 = Controller
2 = Control gear cabinet
3 = Battery switchboard
4 = Field-weakening resistors
5 = Traction motor fan
6 = Contactors for auxiliary motors
7 = Resistance fans
8 = D.C. tap changer
9 = Main circuit-breaker
10 = Grouping and heating contactors
11 = Field-weakening contactors
12 = Compressor

with the main aim of saving weight wherever possible. In the present case the Société Fives Lille-Cail, Le Matériel Electrique S-W and the Brown Boveri associate company Compagnie Electro-Mécanique (CEM), shared this task; CEM undertook to supply all the control gear, and were also entrusted with the layout and erection of the electrical equipment.

The necessity for drastic reduction of the weight enabled some new ideas to be materialized in the sphere of control gear. Some of these are worth describing briefly. Obviously, on a high-powered lightweight vehicle all possible means of utilizing the rail friction must be exploited. Thus, in addition to using single-motor bogies, the method of starting with the two motors in parallel was chosen. Nevertheless, for occasional traction duties requiring reduced speed it is an easy matter to change over to series connection.

Although the slightly drooping speed-torque characteristic of the series d.c. motor tends to prevent wheel-slip, it does demand a very finely graduated starting resistance, in order to keep the abrupt changes in the tractive effort in tolerable limits. But the greater the number of control steps, the more control gear is required. Hitherto electro-pneumatic or electromagnetic contactors combined to form blocks, or cam-operated switchgear driven by servomotors were employed. However, both these methods involve a considerable amount of equipment since every set of contacts has to be fitted with a means of quenching arcs.

Resistance Control by D.C. Tap Changer

For many years Brown Boveri have been making a.c. tap changers for varying the voltage on the h.v. or l.v. sides of the transformer, the switching functions being divided between a multi-stage selector operating at no-load, and a small number of diverter switches capable of interrupting the heavy current. These units, which have been developed to a high state of perfection, are rendering excellent service in numerous traction vehicles at home and abroad. It was an obvious choice to use them to control d.c. vehicles, because they offered a very simple and compact solution. The Brown Boveri traction-type tap changer has already been described in this journal [2]. Adapting it to d.c. operation involves a few constructional modifications, particularly to the diverter switches.

Fig. 9 illustrates how the resistance tappings are connected with the selector segments. The two pairs of brushes, which are moved alternately in steps (*A* and *B*) establish the connection with the busbars

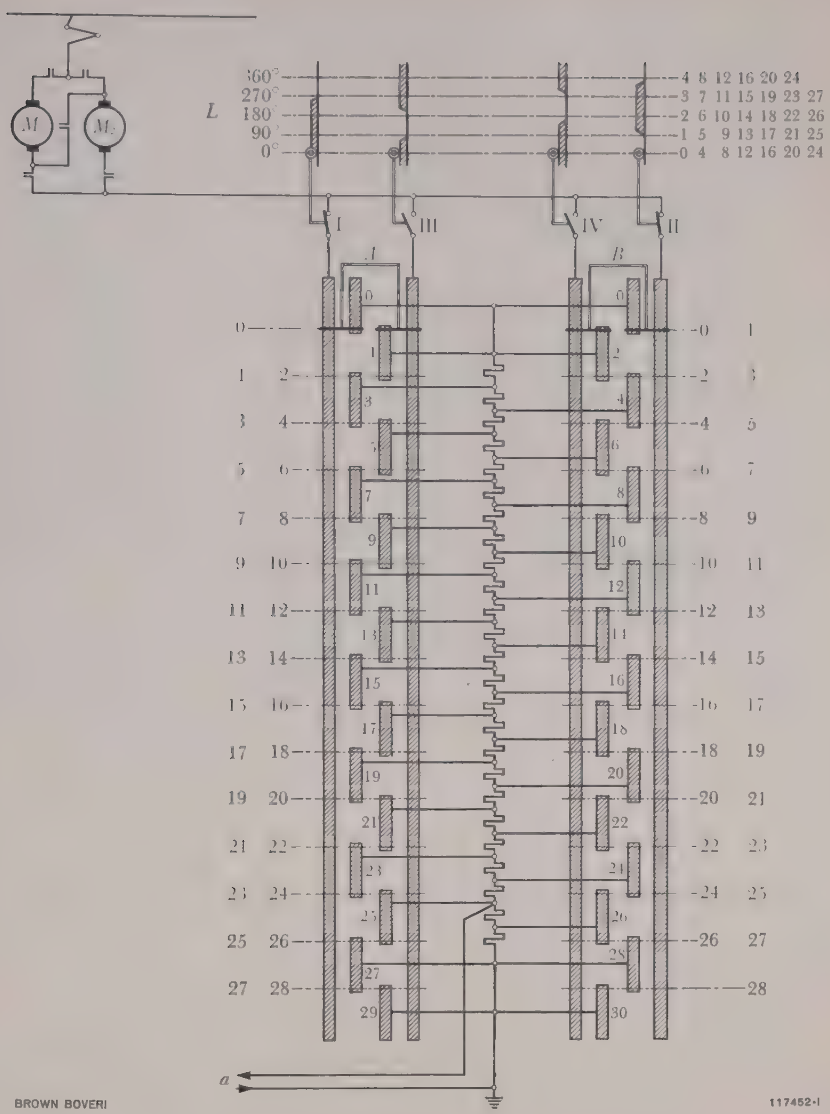

Fig. 9. – Circuit diagram of the tap changer and starting resistors of the B'B' d.c. locomotive No. 9400

The established design of a.c. tap changer was successfully adapted to the requirements of a d.c. traction vehicle. On a multi-stage selector (steps 0–28) the required resistance is picked off by two alternately advancing moving contacts *A* and *B*. Cam-operated diverter switches only permit the current to flow through a contact when it is still.

M_1, M_2 = Motors
L = Diverter-switch cam-shaft
A, B = Selector contacts
a = To the motor of the resistance fan

leading to the diverter switches I and IV. The action of these cam-operated switches is adapted to the movement of the moving contacts *A* and *B* so that this movement is always and only executed when the diverter switches I and III, or II and IV, respectively, are open. For this reason the moving brushes are also actuated by a Geneva gear running off the shaft of the diverter switches, and operated through a reduction gear. The motive power is supplied by a four-cylinder air motor directly coupled with the diverter-switch shaft, every 90 ° shift of which corresponds to the step from one tapping to the next. The air pressure is applied to the cylinders of the motor by electro-pneumatic valves, energized in the appropriate sequence by contacts actuated by the crankshaft of the motor. The air motor and its control valves operate reliably at all pressures and voltages covered by the IEC recommendations for switchgear (Publication No. 77, 1955). The speed of travel varies only slightly with changes in the operating air pressure and is of the order of three steps per second. If necessary, the tap changer can be manually operated from either of the driver's cabs. The transmission system incorporated for this purpose acts simultaneously as a means of indicating to the driver what position the tap changer is momentarily occupying.

Altogether there are 27 starting steps, the first of which includes field weakening. To connect the traction motors in series and for field weakening, electro-pneumatic contactors are employed in this

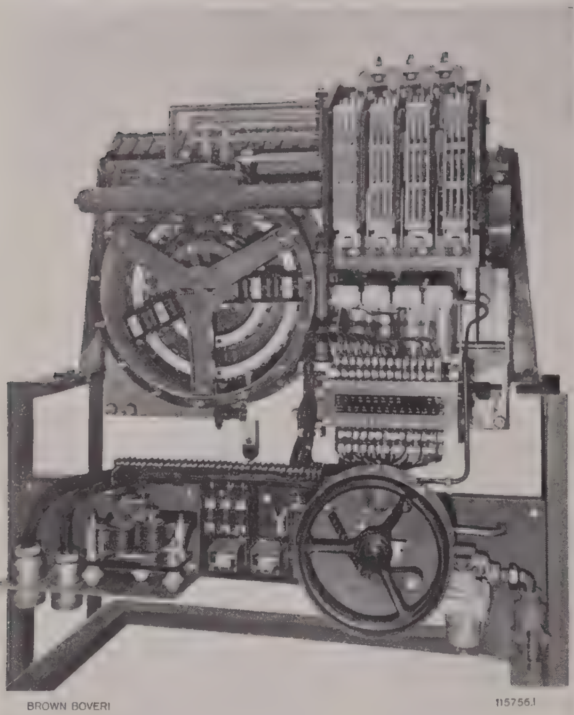

Fig. 10. – D.C. tap changer of the B′B′ locomotives of the 9400 series of SNCF

The large object in the middle of the picture is the circular selector, the front cover of which has been removed. The fixed selector contacts are mostly obliterated by four semicircular collector rings. The rotating arms of the roller contacts are clearly visible. Adjoining the selector at the top right are four diverter switches, beneath which is the four-cylinder air motor and auxiliary contact drum. In the lower part of the frame are the control relays and a handwheel for operating the tap changer direct.

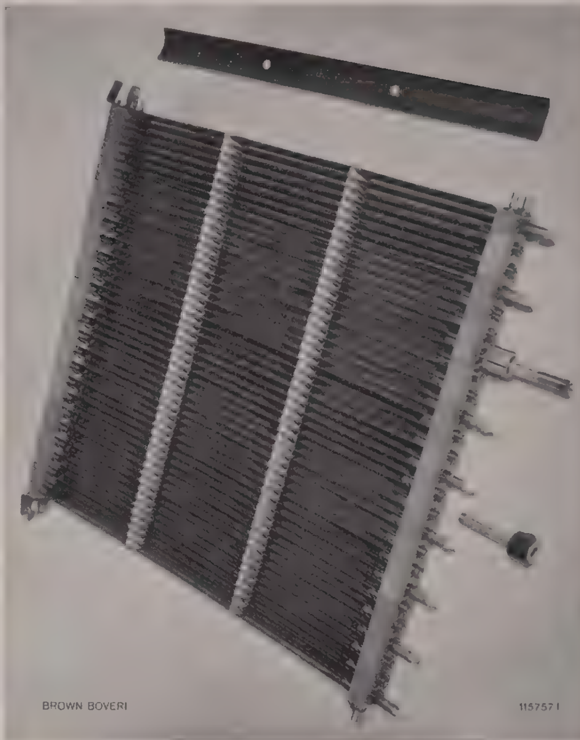

Fig. 11. – Tray section of the starting resistor composed of vane-type elements

Altogether 13 such trays are assembled in a casing by stacking one above the other, and ventilated by a common fan. The plug contacts visible at the front of the picture carry the current to the resistor elements.

particular case. It is quite feasible that, in the course of continued development, these functions will also be taken over by cam-operated switch elements related to the diverter switches.

Fig. 10 shows a combination of selector, load switches, air motor, auxiliary contact drum, control contactors and manual operating mechanism, all mounted on a common frame with a total weight of 550 kg. The space and weight saved in comparison with an arrangement of the classical type is obvious.

Vane-Type Starting Resistors

If, instead of the conventional regrouping of the motors, only the parallel connection is stipulated for starting, the waste heat generated in the resistors rises by about 50%. Since this large amount of energy has to be dissipated in an unchanged starting period, the resistors must be correspondingly reinforced. In order that this may be done without unduly increasing the space occupied and the weight, the vane-type resistors (Fig. 11) recently developed by Brown Boveri were utilized. An article on this remarkable new design appeared in an earlier issue of this journal [5]. Here it may merely be pointed out that these resistor elements are composed of curved sections like turbine blades, made of sheet resistance material, assembled with insulating spacers to form flat, grid-like trays. By mounting several such trays on top of one another, a compact block is formed, through which a strong current of cooling air can be blown, as in a ventilating shaft. Owing to their large surface area and the intense ventilation, it is possible to dissipate a large amount of energy in a small space.

The B'B' locomotives of the 9400 series each contain six such banks of resistors, each with 13 trays. These are carried by slide-rails in the sides of the casing, so that, after removing the front panel for inspection or cleaning, the trays can be withdrawn like drawers. Since each tray only weighs 8·5 kg, this can easily be undertaken by one person. There is no need to disconnect special leads because the current to the resistors is carried by plug connectors at the rear of the casing.

An axial fan mounted on each resistor casing forces air from the machine room through the array of resistor vanes down into the atmosphere. The clearance from the fan outlet to the first resistor element is large enough to ensure a uniform distribution of the air across the entire cross-section of the grid. Since the intermediate chambers of all the casings are interconnected, the failure of a fan is not serious since the resistors continue to be ventilated by the flow of air from the adjoining unit. The locomotive can continue running with its motors in series. The fan motors, as series-wound machines, are connected in parallel up to the last two resistance steps, a system frequently encountered in French locomotives, so that their speed varies with the load current. This method is very convenient as it enables the rate of ventilation to be adapted to the load and the motor to be fed with surplus energy.

Particularly illuminating is a comparison of the new design of resistance unit with an older design, especially as regards space and weight. The old type consisted mainly of corrugated strip wound to and fro on insulating formers, and may be found, for instance, on the $B'_0B'_0$ locomotives No. 9001/2 supplied over ten years ago to SNCF, being regarded at the time as a notable achievement in reducing the weight and the space occupied. Whereas the old design occupied a volume of 0·9 m³ and weighed 400 kg, the modern design only occupies 0·3 m³ and weighs 180 kg, thereby clearly underlining the progress which has been made.

The first locomotive of the new B'B' series, No. 9400, following its completion in the summer of 1959, was subjected to a number of severe tests in subsequent months. During starting tests with very heavy loads, tractive efforts at the wheel tread of up to 29 t were measured, the current carried by the traction motors approaching almost twice the continuous rated figure. The careful dimensioning and high quality of the resistors is borne out by the fact that they were able to withstand such severe overloads without the least trouble. Since then several more locomotives of this series have been completed and placed in service.

Concluding Remarks

The foregoing remarks deal with two traction vehicles that differ completely from one another as regards design and duties, though each represents a remarkable achievement in its particular sphere.

The motor-coach compositions of the Parisian suburbs are typical prototype vehicles. Their advantages and suitability still have to be proved in regular service, before a decision is made regarding large-scale production. The d.c. locomotives, on the other hand, have already been produced in large numbers and are allocated an important share of the extremely varied traction duties in the SNCF programme.

The success of the Brown Boveri pulsating-current motor is largely due to the careful evaluation of all the information and experience gained from the construction of earlier types of motors of this kind. Valuable assistance was rendered by the progress achieved in the field of insulating materials and their applications. Special attention was devoted to the problems of temperature rise and ventilation of large, self-ventilated machines.

The construction of the d.c. tap changer was successful from the very start. This is without doubt the outcome of many years experience gained from the development of tap changers for a.c., available in the form of carefully designed and well planned components.

Finally, the resistors were quite a new venture. Problems associated with the materials and production were predominant in this development programme. Both the active resistance material and the ceramic insulating members must be able to withstand severe thermal and mechanical stresses. Careful studies had to be carried out to find the most reliable and durable combination of a wide variety of metallic materials. Extensive tests proved the suitability of the solutions arrived at.

The design of the vehicles involved a hard fight to gain advantages with regard to space, weight or power. Engineering has made a large number of single steps in attaining its present standard. From the foregoing remarks it may be gathered that encouraging progress has been made in recent years. It is to be hoped that the aims set for the future will be likewise attainable.

(KME) A. FEHR

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ADVANCED MANUFACTURING TECHNIQUES IN THE SPHERE OF MERCURY-ARC CONVERTERS

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The increased employment of mercury-arc converters in modern drives is accompanied by heavier demands on the load capacity, which can only be fulfilled by the adoption of manufacturing techniques based on the results of advanced research. The various stages in the course of the evolution of such techniques are described in the present article.

General Aspects

The tanks of mercury-arc rectifiers (or inverters, for which reason they will subsequently be referred to as converters) are high-vacuum vessels made of sheet-steel free from flaws, from which the electrodes emerge through insulated bushings with vacuum-tight seals. Since such units are nowadays mostly operated without a vacuum pump, with pure mercury at pressures between 10^{-3} to 10^{-1} Torr, and they are expected to have a useful life of more than 15 years, the conditions stipulated regarding the design and manufacture of tanks must take into account this life and the electrical duty during it.

In view of the increasing preference for the employment of such static converters in recent years, particularly for high-power variable-speed drives, and having regard to the greater severity of the duty imposed by such applications, Brown Boveri have had to carry out an extensive programme of research and development, in the course of which the mercury-arc converter has become a reliable, efficient unit, fully adapted to the new requirements.

With the formulation of a duty theory by Wasserrab [1–5], and the joint consideration of discharge phenomena and circuitry on which it is based, it became possible for the first time to bring under control the most undesirable cause of trouble in static converters in a wide range of operating conditions, i.e. backfiring. From these general considerations thereby introduced into the converter field there arose far-reaching consequences for the construction of modern mercury-arc converters, as indicated in two of the articles referred to in the bibliography [6, 7].

In conformity with the wide variety of problems associated with the development of such converters, the scientific and technical investigations proceeded on the widest possible basis. Even portions of the field have received special treatment, in accordance with their practical importance, for example the investigation of physical or technical phenomena in low-pressure gaseous discharges in the steady or unsteady state, or effecting improvements in relevant vacuum techniques and technology.

The planning of a manufacturing process adapted to the requirements of subsequent converter operation is a field where much valuable knowledge has been gained, leading to considerable changes, all with the object of keeping the frequency with which backfiring takes place as low as possible—even with the greater duty to which the tanks are now subjected. Notable progress was made in this respect and the capacity and reliability of converters was brought to a very high standard.

The remarks that follow give a brief review of the results achieved as regards present manufacturing techniques in the field of mercury-arc converters, of the problems encountered and the manner in which they were handled in the Brown Boveri rectifier factories and laboratories.

Selection and Treatment of Materials up to Assembly of the Converter Tank

For the design and construction of mercury-arc converters the choice of materials is based on quite different requirements to those for conventional machines. Of course, the same aspects regarding the choice of material have to be taken into account, since the converters, particularly the larger types, are heavy units, but nevertheless, for such a high-vacuum design, the main requirements concern vacuum techniques and the physics of gaseous discharges. They may relate to the preliminary treatment and the process of evacuation, or to the properties peculiar to an inhomogeneous metallic construction in which different kinds of metals are combined with ceramic materials and glass.

Of the three principal materials employed in the construction of converters—graphite, mercury and steel—the quality of the valve is determined above all by the graphite which, on account of its high melting point, its good heat radiation qualities and its low vapour pressure, is an ideal material for the anode and grid. To eliminate the harmful centres of electron emission on its surface, the specification for graphite calls for a minimum of alkalis and rare earths—known from the manufacture of oxide-coated cathodes for electron tubes—and other impurities with a low electron work function. Apart from this important factor of purity of the materials, the choice of graphite is mainly governed by the manner in which a compromise is struck between a number of physical requirements, some of which even contradict one another. These include low porosity, rapid degassing, homogeneous, smooth non-sputtering surface [8] and good thermal radiation; to these may be added high thermal and electrical conductivity, adequate mechanical strength and machinability. Regardless of these properties, specified from the start, the finished graphite components are nowadays almost all heated in a vacuum to 1800–2200 °C, and finally, before being assembled in the valve, are stored in a vacuum or protective gas, free from all dust. By carrying out intensive research (Fig. 1–3) Brown Boveri are making every effort to find the best solution as regards material for their converter anodes for all kinds of operational conditions, either by expedient choice of the materials or by subsequent special treatment.

Just as important as the purity and correct choice of the material for the anodes is the freedom of the surface of the material from impurities arriving later as they might first encourage electron emission and, finally, backfires, especially when particles of insulating, but at the same time semi-conducting impurities (glass, quartz dust, emery powder, products of sputtered igniter rods, etc.) are present. In the phenomenon known as "Spritzentladung" [9] or the similar "Malter effect" [10] the ions striking such a particle of insulating material at the beginning of the anode blocking period are retained as a positive charge on the surface, thus producing an electric field in this insulator with such a high field strength that electrons are even emitted by cold anode surfaces, which fly into the gas-filled space without first neutralizing the ions at the surface of the

a

b

c

Fig. 1. – Treated anode graphite

As photographed by an electron microscope. Enlarged 6000 times.

a: before ion bombardment
b: after ion bombardment equivalent to years of converter service
c: surface unable to resist ion bombardment

insulator. This electron emission from thin insulating layers has recently gained a certain amount of prominence in the development of cold cathodes for amplifier tubes [11, 12], clearly demonstrating its danger in mercury-arc converters. Since such particles of foreign matter repeatedly find their way to the surface of the anode [9, 13, 14, 15]—due to sputtering and as a result of their becoming negatively charged during the discharge period, or the entry of neutral gas into the anode space—it is understandable that, in addition to ensuring that the anode components are perfectly clean, the tank itself and all its individual parts require very careful cleaning.

Mercury, which is an ideal material for the cathode and as charge carrier, owing to its favourable vapour-pressure curve and its low melting point, must have all traces of foreign matter removed (especially other metals dissolved in the mercury, or residual dust, oil and moisture) by repeated filtering, washing and chemical treatment, followed by distillation in vacuum.

Special treatment is also required by steel, first introduced into the construction of static converters by Brown Boveri 50 years ago as a material for the tank walls. Like graphite it is also completely passive with respect to mercury. During the development to the large mercury-arc rectifier, started by this

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Fig. 2. – Investigation of surface phenomena associated with the physics of gaseous discharges, using different graphite specimens

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Fig. 3. – Investigating the absorption or emission of gas by graphite specimens in atmospheres of different gases at different pressures

The object of such investigations is to derive the most effective manufacturing procedure, from the aspect of vacuum techniques, in the construction of mercury-arc converters.

remarkable step, the immediate aim of which was to replace the motor-generator set by a simple means of producing direct current, the design and manufacture were carried out almost exclusively in accordance with the principles of machine design and the construction of containers. Following the development from the unit with a complete set of pumping equipment via the pumpless tank (at the time only visualized for pure rectifying duties) to the heavy-duty static converter controlled almost exclusively by grid control, i.e. a high-vacuum unit with an extremely high output capacity and reliability, the aspects governing the choice of materials and their treatment became quite different. Even the steel used for the tank walls has to comply with extremely strict requirements as regards homogeneity and definition of the material, as well as the quality of the surface exposed to the high vacuum. Generally steel plate free from inclusions and cavities is specified, with properties which have been thoroughly tested, in particular the composition (Fig. 4, 5, 12, 17) to ensure that it has a low carbon content and is practically free from sulphur, phosphorus and other harmful impurities. With water-cooled pumpless converters in particular, hydrogen from the cooling water must be prevented from diffusing through the steel walls by making the latter of a material impermeable to atomic hydrogen, or a corrosion-resistant material (e.g. by suitably alloying or by pre-treatment), or by employing laminated walls. Likewise for all thermally stressed steel components, low-carbon steel is used and it is characteristic of the manufacturing process that these parts also have to undergo heat treatment in a controlled atmosphere and vacuum (Fig. 6, 7). The temperature, though, is much lower than for the graphite, being only of the order of 600–1000 C. When the metal parts have been perfectly cleaned and degassed they can be easily stored, like the graphite parts, in a vacuum container or in a dry, protective gas.

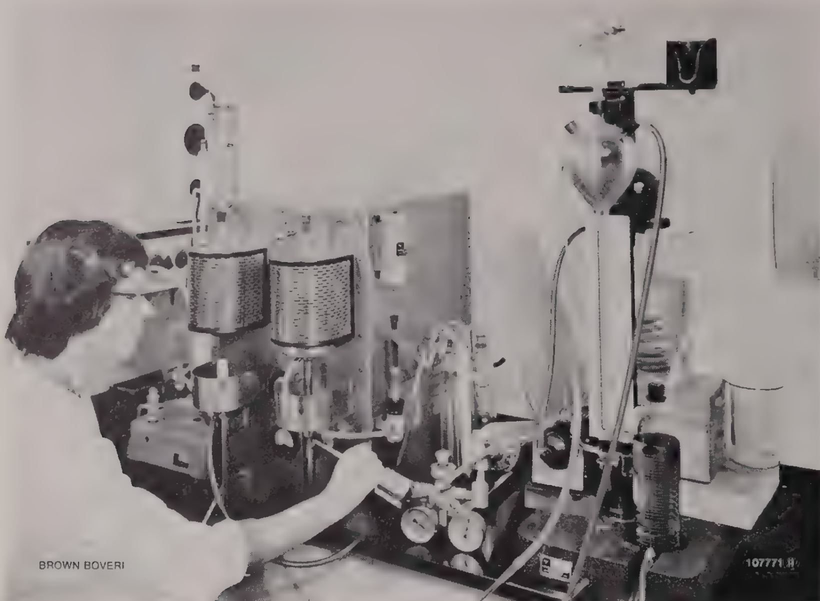


Fig. 4. – Apparatus for rapidly determining carbon and sulphur

Fig. 5. – Metallographic laboratory, with the two metal microscopes in the foreground

The glass and ceramic parts, also the enamels, a decisive factor in the choice of which is the coefficient of thermal expansion of the components of a joint over the entire temperature range encountered in the course of manufacture, have to conform to very stringent regulations as regards quality and treatment. This mutual adaptation of the sealing materials has been satisfactorily solved for all diameters met in

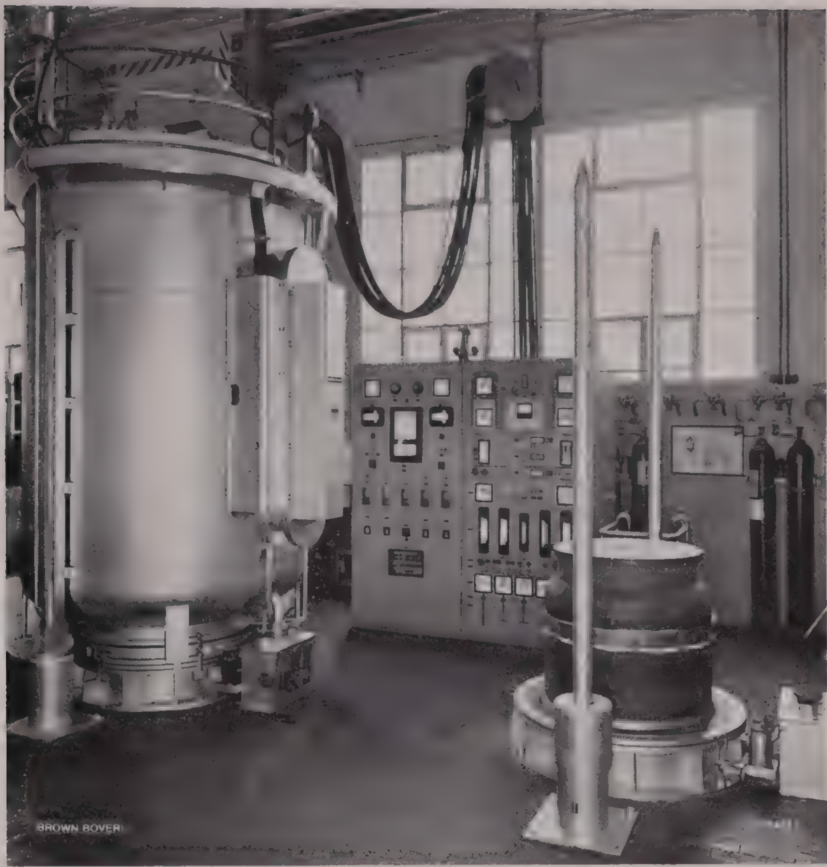


Fig. 6. – Vacuum furnaces used for degassing metal parts in a controlled atmosphere

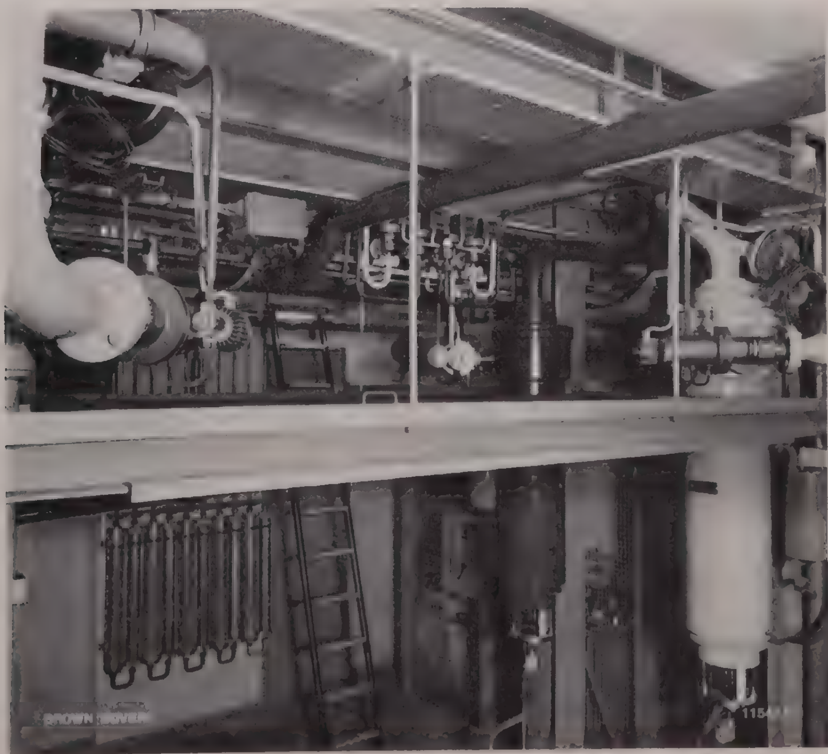


Fig. 7. – Accessories of the vacuum furnace, used to obtain a controlled atmosphere

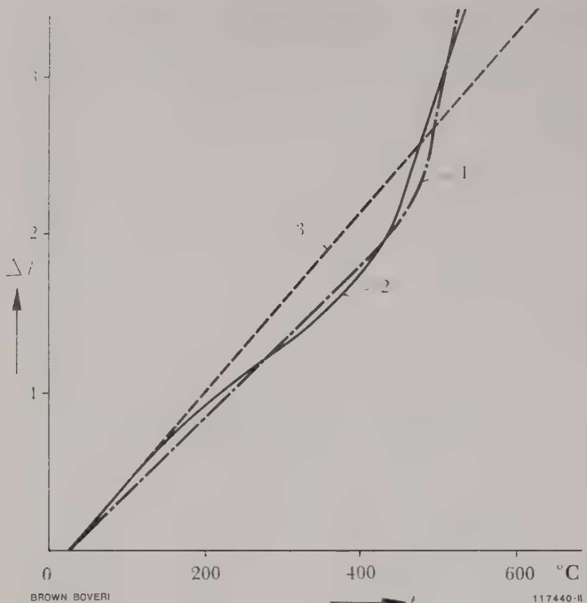


Fig. 8. – Curves showing the expansion Δl (in mm/m) of Kovar-glass, Kovar and molybdenum

1 = Kovar-glass
2 = Kovar
3 = Molybdenum

practice in the construction of static converters, and for all thermal and mechanical stresses. The pre-stressed glass [16] and tubular glass seals [17], the latter based on Kovar (an alloy containing iron, nickel and cobalt) and Kovar-glass (Fig. 8–10), as well as the ceramic seals, have been brought to a high standard of reliability—with respect to their vacuum-tightness, resistance to temperature variation and ageing—and the sealing process chosen by Brown Boveri in each particular case is the one which best suits the purpose for which the converter is to be used. With the exception of the graphite, all parts of the converter, after assembly, are subjected to a multi-stage washing process to remove all traces of grease and other contamination.

In addition to the extremely clean and exhaustive preliminary treatment of all components, adequate precautions must be taken during the assembly of the converters to avoid such impurities as dust, oil, grease, sweat, etc. Final assembly is therefore carried out in specially air-conditioned rooms, using protective gloves and clothing, tweezers and manipulators, and in the shortest possible time before ultimate evacuation. Clean and rapid assembly is one of the most important stages in the manufacture of a converter and is decisive for the quality of the finished product.

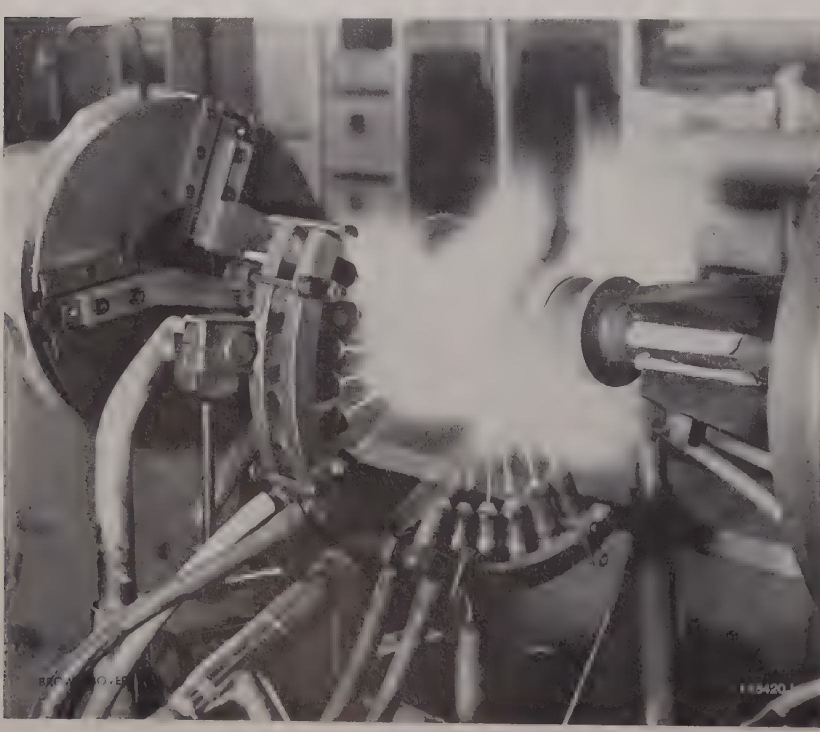


Fig. 9. – Making a glass seal with flames, a ring of burners being used to fuse glass and Kovar together on a lathe

Vacuum Quality and the Technique of Evacuation

With all kinds of electron emission from the surface of a converter anode [1, 9, 18]—be it thermionic emission (e. g. due to strong general or local heating, or the presence of particularly emissive impurities), field emission (e.g. due to insulating particles becoming charged), or secondary electron emission —for a backfire to take place at all it is at least essential for the liberated electrons, following their acceleration by the positive space-charge zone—in front of the anode during the blocking period—to find a sufficiently high gas density. It is then largely the result of repeated variation of ionization, plasma density, space-charge layer thickness, energy input and superficial electric field strength—and its effect on the electron emission—depending on the local gas density, whether flashover to a self-sustaining spot discharge will take place in the form of a backfire. While every effort is made to prevent such an occurrence by ensuring that the neutral gas in the anode space has a permissible density, provided this originates from the mercury vapour [14, 15, 19, 20, 21], by adopting an expedient design and cooling system for the tank, the density—as far as other gases are concerned [6, 22, 23]—must be assured by imposing strict requirements regarding the vacuum-tightness and freedom from foreign gases, i.e. by the derived manufacturing process.

By adopting a weldable design and welding all parts of the tank walls by the argon-arc or atomic arc process (shielded by an inert gas containing no oxygen or moisture) and by changing from manual to automatic welding [16], also employing the previously mentioned vacuum-tight, heat-resistant electrode seals [16, 17, 26] and by up-to-date methods of testing materials, it is possible to attain a total residual leakage remaining almost constant at less than 10^{-9} Torr. l/s, even after numerous, rapidly alternating thermal stresses on the entire converter tank, with temperature changes of several hundred degrees.

Testing the Vacuum-Tightness

For quantitative determination of the overall leakage of a converter tank, as well as for the location of individual pores, successful results have been obtained for a number of years using leak detectors based on the principle of the sector-field mass spectrometer and employing a gas (helium) not normally encountered in the test object [16, 24]. As a rule the measurements of total leakage from tanks prepared according to the foregoing principles was even less than the lower limit which can be determined in practice, namely about 10^{-10} Torr. l/s. However, from the technical aspect this result is uninteresting because a value of 10^{-9} Torr. l/s completely fulfils the most stringent requirements for any kind of operation likely to be encountered nowadays.

A test method employing a chemically active test gas at a slight excess pressure and an indicator cloth, placed particularly over the outer welds, has proved quite good as a means of testing for leakage, e.g. for inspecting the tightness of the electrode seals before they are finally welded into the tank. A

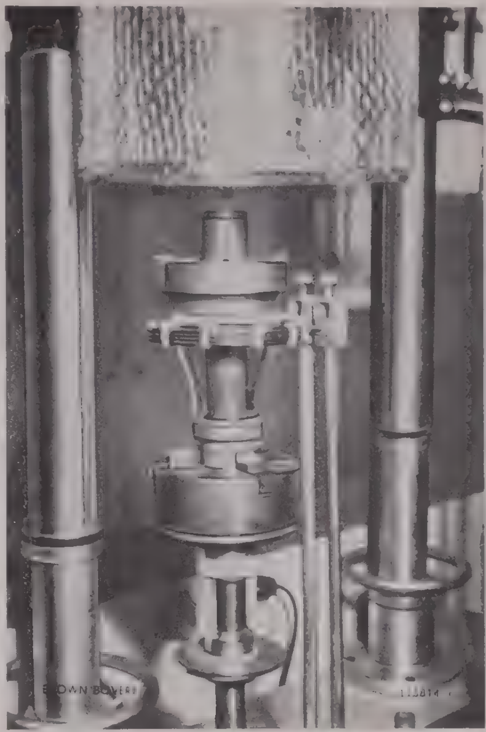


Fig. 10. – Kovar-glass seal of an anode bushing, fused by r.f. heating

The glass bell (shown raised in the picture) allows the seal to be bathed in a stream of protective gas.

Fig. 11. – Photoelastic stress analysis of fused glass-metal seals in a polariscope

characteristic feature of this method is the integral effect of the indication, in that the colour change is cumulative with time, and immediately above a pore. By allowing the gas to act for a long time, especially when the indicator cloth is properly prepared, it is also possible to approach the sensitivity of the mass spectrometer method responding to the momentary concentration of the test gas.

Converter tanks repeatedly tested by these extremely sensitive methods at different stages during manufacture, with a total leakage of 10^{-9} Torr. l/s and a tank volume of, say, 50 l, will have an annual pressure rise of less than 1 mTorr. For a converter tank to exhibit vacuum-tightness of this order is an adequate assurance that it will give many years' dependable service, together with the necessary freedom from foreign gases [23], provided the internal components are kept equally free from gas by observing similar strict rules for manufacture and testing.

Evacuation of the Converter Tanks

If it were possible to rely solely on the evacuation of the inherently gas-tight tank by reducing the internal pressure to the level of about 10^{-5} to 10^{-6} Torr by pumping, this process would be finished in a few hours. But since all components have a certain amount of gas adsorbed on the surface, and occluded, dissolved or chemically bonded inside, which, even with the steel parts used, may amount to a multiple of the actual volume of the part (referred to atmospheric pressure), and are only given up very slowly by such metals, even at high temperatures, the final degassing process is an extensive and costly business, involving a number of separate processes depending on the stage of completion.

This is taken into account in the construction of Brown Boveri converters in that, right at the start, when the raw materials are being selected, stress is laid on a low gas content [24] of the most important components (Fig. 12). Also by employing walls as thin as possible, the diffusion distance is minimized. Apart from the heavy expense involved in cleaning and keeping the internals clean, a large outlay is involved in the vacuum ovens for preliminary degassing of the components (Fig. 6 and 7). As a result of these measures and subsequent degassing processes it is possible to attain still more complete freedom from foreign gas, thereby enhancing the reliability of the converter.

Among these subsequent degassing processes, the first is the heating of the entire welded and gas-tight tank in an oven, during which the liberated gases are continuously pumped off and their quantity

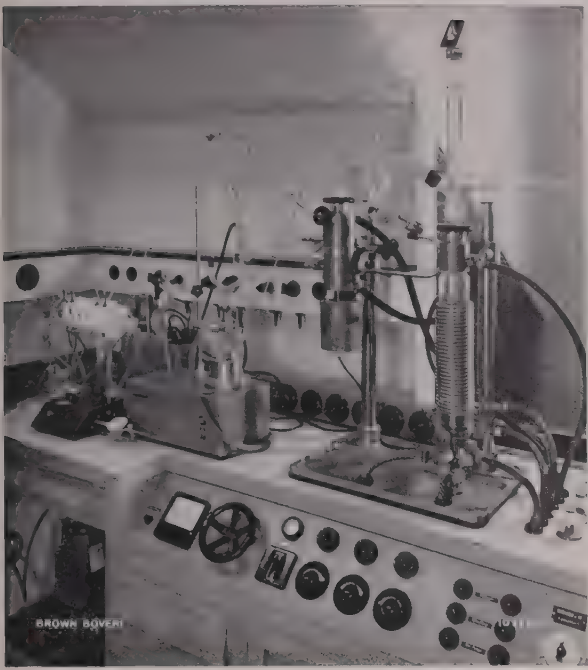


Fig. 12. – *Apparatus used to determine the gas content of metals*

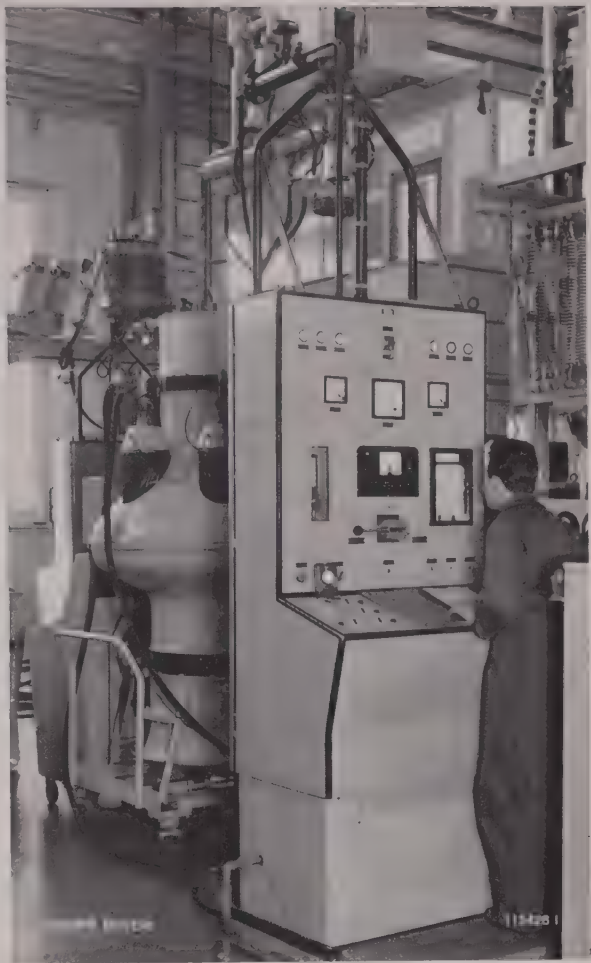


Fig. 13. – *Degassing a mercury-vapour converter tank by passing a heavy current and simultaneously pumping ("electric formation")*

measured. Whereas preliminary degassing is primarily governed by the rate of diffusion of the gases still contained in metal components, especially those which are later heated in service and require as high a temperature as possible for the heat treatment, but on the other hand is characterized by a constantly low degree of evaporation of the parts to be degassed and their absolute dimensional stability, baking out the finished tank requires a temperature only slightly below the point at which the electrode seals soften. For this reason alone it would be insufficient merely to degas the internals by evacuating the heated tank with a pump, i.e. with no preliminary degassing in a vacuum furnace. Moreover, it would unnecessarily prolong this and the succeeding pumping processes.

Since when assembly is performed quickly, metal parts which have been previously degassed, in contrast to graphite, absorb relatively little additional gas, and that mainly at the surface, and these superficial layers of gas and moisture can be driven off quickly at the present baking temperatures, leaving a remainder which is harmless for subsequent operation, the Brown Boveri multi-stage degassing plant fulfils all requirements as regards vacuum techniques. This is all the more evident as, during the subsequent "electric formation" (Fig. 13), a definite, sometimes quite appreciable proportion of the gases still contained in the tank (Fig. 14) is carried into the colder steel walls, owing to the gettering effect to the arc, instead of being completely pumped out.[1] This is the reason for the stipulation, so important in the manufacture of static converters, that the internals should be freed as far as possible from getterable non-rare gases before the formation

[1] During "electric formation" the anodes in particular, and the parts situated directly in the discharge zone, are heated by the passage of a heavy current, the vacuum pump being kept continuously in action, until finally the amount of gas extracted becomes negligibly small.

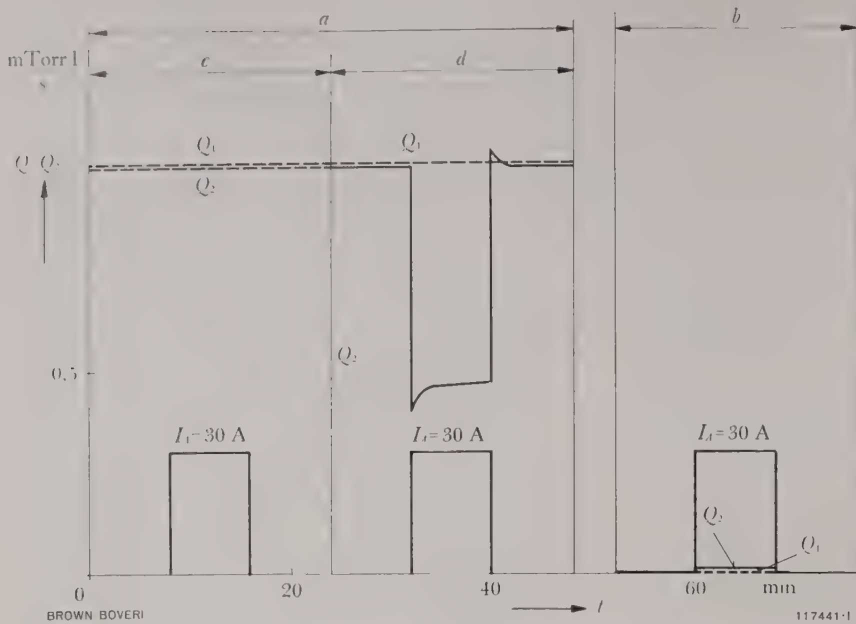


Fig. 14. – Explaining the gettering of gases by the steel walls of a mercury-arc converter during the process of formation [23]

showing the amount of gas Q_1 flowing into the anode space, simulating a definite rate of emission of gas by the anode graphite, and the rate of flow Q_2 of gas through the pump line at low anode current I_A (temperature $T_k = 25$ °C)

a = With gas flowing in
b = Without gas flowing in
c = Argon
d = Air
t – Time

process, i. e. the main degassing operation should take place during the earlier processes of heating the components in vacuo and baking out the assembled tank with the pump in action.

During the formation the residual gases, which re-entered the porous graphite of the anodes during assembly of the tank and were not driven off by baking out the tank, have to be finally removed by heating the anodes to several hundred degrees above their intended operating temperature, by employing a formation programme which reduces gettering of foreign gases to a minimum, and by pumping them out of the tank.

In this connection it is worth mentioning the numerous elementary processes and macroscopic phenomena in an arc plasma of this kind and at its boundaries, because they, after all, form the basis of the final degassing process. This not only includes the operations taking place directly on the electrodes or the walls of the tank, in particular the release, exchange and bonding of gas, but also the gas and surface reactions accelerated by the activation of the gas (dissociation, excitation, ionization) in the discharge space itself or at the steel wall. Owing to the complexity of all these elementary processes, it demands a great deal of skill to find a formation programme which takes into account all these factors. Nevertheless, following systematic investigations, it has been developed to a high standard in the Brown Boveri works. Its effect on the quality of the valve, and thus on the standard of the product is quite considerable. The freedom from foreign gases thereby attained can be improved still further by storing the graphite parts in protective gas from the time they are heated in vacuo until they are assembled in the converter tank.

Gettering and the Life of Pumpless Converters

Having finally reduced the amount of gas emitted to such a low level, additional operations can be performed, such as sealing the pumping tube, followed by quality checks. Every converter is subjected to a quality test to establish its anode blocking capacity with a probability of backfire of $W < 10^{-10}$. The object of this is to ensure that, on the average, less than one backfire will occur in one year's continuous operation at 50 c/s in a converter having six anodes. Likewise, after the pumping tube has been sealed off, the tank is tested for the presence of undesired foreign gases by means of an extremely sensitive test method, to make sure it complies with the stipulations regarding leakage. Finally it is im-

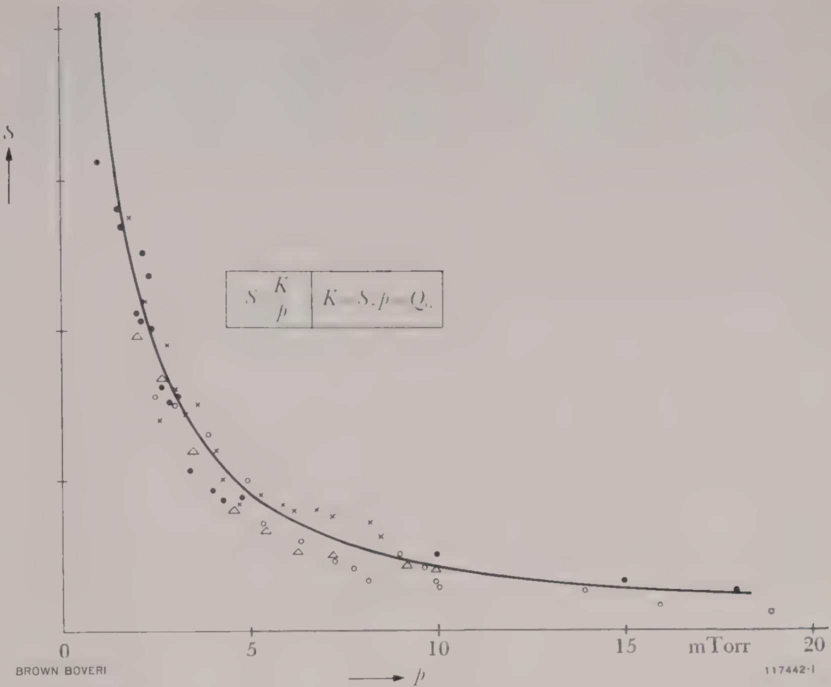


Fig. 15. – Pumping (gettering) speed S of a mercury-vapour discharge for the non-rare permanent gases of atmospheric air in terms of their partial pressure p at constant anode current I_A [23]

● ○ Points measured at the start of the test

× △ Points measured after gettering 260 Torr.l of air

portant to gain some knowledge of the extent of the gettering effect of the arc on residual gas subsequently released as a result of ion bombardment or the slight subsequent emission from hot internal parts. This is indicated by the fact that, in numerous cases, a getter has been incorporated for such gases in the converter tank.

Owing to the vacuum treatment of the tank, as already described, Brown Boveri converters possess gettering properties comparable with a vacuum pump, without any special equipment or the incorporation of additional parts, especially in the presence of an arc. As a means of expressing quantitatively the extent of gas gettering, long known qualitatively—for the gases O_2, N_2, CO, CO_2, etc.—by steel-tank mercury-arc converter discharges [25, 22], it may be allocated a pumping (gettering) speed S (analogous to the description of pumping processes in the construction of vacuum pumps) and a gettering rate Q_G resulting from S and the partial pressure p

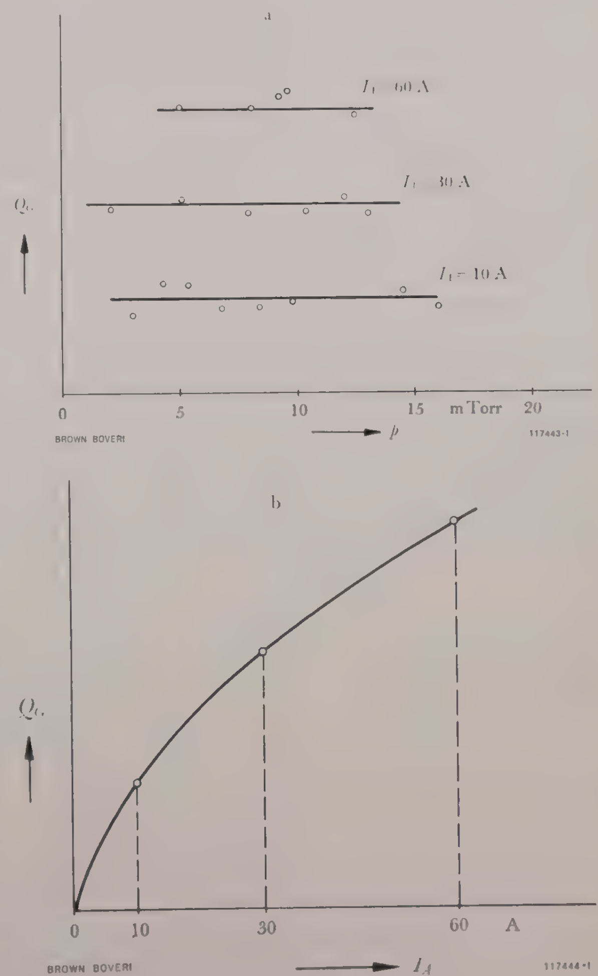
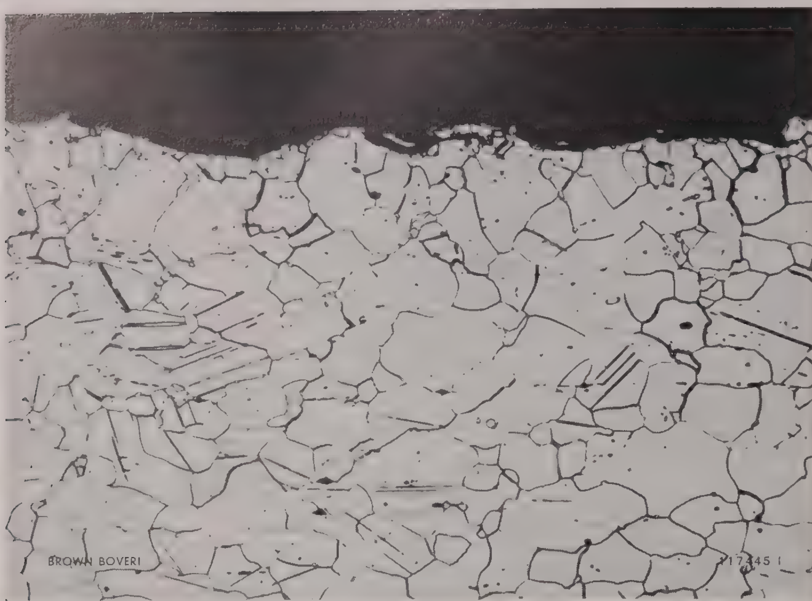


Fig. 16. – Gettering rate Q_G of a mercury-arc converter for the non-rare permanent gases of atmospheric air in terms of their partial pressure p (a) *and the anode current I_A* (b) [23]



a

b

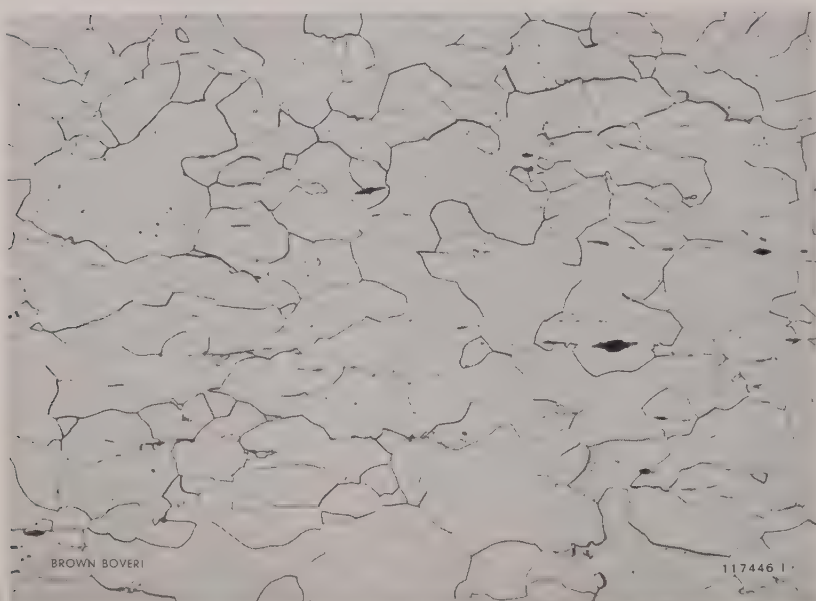


Fig. 17. – Structure of the steel walls of a mercury-arc converter (enlarged 200 times)

a: Near surface after gettering quite a large amount of air, notable for the nitride needles within the grains.

b: Further into the metal there are no signs of nitrogen separating out in the form of nitride.

of the non-rare permanent gases [23]. The relationship is thus $Q_G = p \cdot S$. In mercury-arc converters, at least at low load currents and for the proportion of non-rare permanent gases in the atmosphere or pure nitrogen, the gettering speed S is inversely proportional to p (Fig. 15) and, even at currents as low as 30 A, can be increased to a rate of 8–10 l/s or more (at $p = 1$ mTorr). For oxygen the figure is many times higher. But since the gettering rate Q_G is not dependent on the partial pressure p (Fig. 16), any foreign gases which may subsequently appear will be absorbed by the walls of the tank at a rate of 8–10 m Torr. l/s, even at the low current of 30 A, regardless of the partial pressure p. This rate is many times higher than the possible rate of emission, under the most unfavourable circumstances, so that proper treatment of the tank and expedient direction of the flow of mercury vapour are alone sufficient guarantee of an adequate vacuum being permanently maintained in the tank.

In further systematic research work concerned with the gettering of gas in mercury-arc converters, definite currents of atmospheric air were deliberately introduced into such tanks. It was thus possible to prove experimentally that, in a correctly designed and properly treated valve, the generally non-getterable rare gases in the air (e.g. argon) attain an inadmissibly high level before the gettering rate Q_G of the steel wall begins to decrease inadmissibly or the equilibrium pressure of the non-rare gases rises excessively, leading to the anode losing its blocking capacity, as a result of which the valve is rendered ineffective [23]. In view of this accumulation of rare gases in the discharge tank, the life t (in years) of a converter valve treated as described is governed by the magnitude of the leakage Q_L (m Torr. l/s), the volume of the tank V (litres) and a maximum permissible partial argon pressure p_E (mTorr) additional to the original rare-gas filling. It may be expressed by the formula

$$t = \frac{p_E\, V}{3{\cdot}15\, \gamma Q_L \times 10^7}$$

in which γ is the volumetric percentage of rare gas in atmospheric air (0·93 %). Of course the products of reaction with non-rare gases have to be dealt with separately in such a calculation (Fig. 17). Here too it can be seen that, with the stated manufacturing procedure and the strict stipulations regarding the vacuum-tightness, freedom from foreign gases and cleanliness, it is possible to attain an almost unlimited life for pumpless converters.

Concluding Remarks

A decisive influence on the quality of static converters is exerted by the choice of materials and the manufacturing procedure. Realization of this important factor has enabled Brown Boveri to make considerable progress in recent years in the construction of converters, not only as regards materials but also in the sphere of process techniques and quality control.

Within the scope of a broad-fronted research programme a large number of process variations and combinations were investigated in conjunction with the relevant quality of the final product. By introducing suitable characteristic values, it was possible to obtain an objective basis for assessment, which finally provided the conditions necessary for the establishment of a technically and economically optimum manufacturing procedure. The knowledge gained has led to appreciable revision of the procedure, as well as to major improvements in the capacity, reliability and life of static converters.

(KME) M. J. Schönhuber

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RADIATION-COOLED TRANSMITTING TRIODES FOR INDUSTRIAL APPLICATIONS

621.385.3

In order to meet industrial requirements, especially with regard to the construction of r.f. generators for welding plastic materials, transmitting tubes have been developed which are not only robust and economical in service, but above all need no special cooling system. By expedient design and choice of materials it has proved possible to construct high-power industrial triodes with a dissipation of several kilowatts, which are simply cooled by radiation. A special feature of these tubes is, moreover, that they are ideally suited to the load fluctuation characteristic of operation in industrial generators, and are still capable of producing a reserve of power. They are therefore very reliable and have a long life.

IN ADDITION to the radiation-cooled transmitting tubes of low output used in communications and industrial generators, i.e. the classical designs such as types T 50–1, T 100–1, T 150–1 and T 300–1, for anode dissipations (P_a) of 50, 100, 150 and 300 W, respectively, it has been found necessary to construct tubes for higher frequencies and industrial applications. This development led to a new range of Brown Boveri radiation-cooled triodes, beginning with the types T 130–1 (P_a=135 W) and T 350–1 (P_a = 350 W), with oscillator output powers of 500 and 1100 W, at frequencies of 200 and 150 Mc/s, respectively. The most common applications for these tubes are in the preliminary stages of telegraphy transmitters or as oscillator tubes in industrial high-frequency generators, in diathermy apparatus or industrial ultrasonic equipment. In self-excited oscillator circuits triodes are generally better than tetrodes, and are usually given preference.

With the expansion of the applications of industrial r.f. generators, especially those used for welding plastics, requiring powers of the order of 1–4 kW, it proved necessary to have tubes of this capacity available, which are cooled in the simplest conceivable manner, which are small in size, require no attention and are favourably priced. Using such tubes it becomes possible to construct generators which are low-priced, robust, simple to operate and have an economical consumption. Certainly there are tubes available for the power range mentioned, but they are cooled by forced draught or water and, consequently, on account of the additional outlay and higher price, are less suitable.

New Radiation-Cooled Tubes for High Outputs

The above requirements are best fulfilled by radiation-cooled tubes requiring no additional cooling system. The aim was therefore to develop such tubes in the direction of higher outputs, in the course of which a number of new problems had to be overcome, in particular the anode dissipation. Thorough investigation of the overload capacity of the grid and anode, of the shape and nature of the glass envelope, and so on, had to be carried out. The outcome of this work is that the new tubes, types T 1000–1 and T 2000–1, both of which are radiation-cooled triodes, can be introduced (see Fig. 1 and 2). They are able to exert a beneficial influence on the design of r.f. generators of small and medium capacities. These relationships can best be explained by a description of their electrical and mechanical properties.

Special Technical Features of the New Radiation-Cooled High-Output Triodes

It does not have to be specially mentioned that the new tubes have a thoriated tungsten filament, affording the advantages of lower heating power with

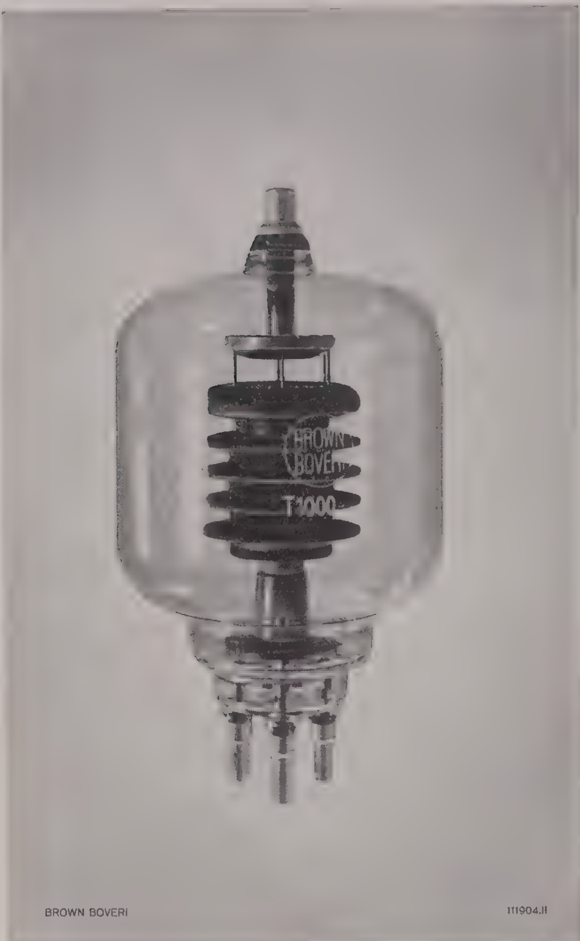


Fig. 1. – Directly heated, radiation-cooled industrial triode type T 1000–1 with an output power up to 3·1 kW in oscillator circuits

Fig. 2. – Directly heated, radiation-cooled industrial triode type T 2000–1 with an output power of up to 6·4 kW in oscillator circuits

increased efficiency. The cathode is so abundantly dimensioned that fluctuation in the filament voltage by as much as +5, —10%, as may be experienced in practice, is quite permissible. As already stated, special attention was devoted to the design of the anode, because it has to dissipate a considerable amount of power through the glass envelope to the surrounding atmosphere, without the electrodes or the seals becoming overheated. As shown in the illustrations above, the solid graphite anode has an enlarged surface with cooling grooves to assist radiation. Owing to its high thermal capacity, an anode of this design is in a much better position to withstand overloads of brief duration. To locate the anode, and forming the connection with the anode cap, molybdenum rods are used, having a low electrical impedance and low thermal conductivity. This and the employment of the prescribed broad-vaned connectors help to keep the temperature rise at the anode seal within the permitted limits, even when heavily loaded. Special care was devoted to the choice of glass for the large envelope. Only first-class specially toughened glass which remains unchanged at temperatures up to 200 °C could be considered. The electrode leads, and the grid and cathode pins brought out through the base of the tube were kept short, thus not only minimizing unwelcome inductances, but also keeping the amplitudes of vibrations

as small as possible, thereby rendering the tubes insensitive to the vibration which is bound to occur in industrial service. All bushings at the base and for the cap are in the form of glass-Kovar seals. Kovar is an alloy containing mainly Fe, Ni and Co, with roughly the same coefficient of expansion as toughened glass. To improve the conductivity, the base pins are silver-plated.

An important feature of the new tubes is that, owing to the very high thermal capacity of the anode, and to the grid and cathode being over-dimensioned, they are ideally adapted to the fluctuations in voltage and load encountered in industrial service. It thereby becomes possible—in contrast to tubes of the classical design, or with external anode—for up to twice the rated load to be carried for brief periods, an advantage which is greatly appreciated in intermittent pulsating operation, as used for many plastic welding processes.

Possible Applications in Practice

With one tube type T 2000–1, which can be operated in an oscillator with an anode voltage of 5·5 kV to produce an output of 6·4 kW, it is possible to construct an r.f. generator capable of producing at the load 4 kW continuously and double this output, i.e. 8 kW, for brief pulses. If the same output were to be aimed at using air or water-cooled tubes as employed hitherto, it would be necessary to choose a tube for a continuous output at the load of at least 6 kW, or a maximum anode dissipation of 8 kW approximately. Apart from the heavy expense for the cooling system and the higher price of the tube itself, a solution of this kind would be less efficient and would have a continuously higher filament heating power consumption.

Doubtless the two new radiation-cooled industrial tubes will help to encourage the development of new high-frequency generators. Whereas the tube T1000–1 offers quite good prospects for small industrial generators up to 2 kW (Fig. 3) and for diathermy apparatus, the tube type T 2000–1 is ideal for generators with a rating of up to 4 kW or, when connected in parallel, up to 8 kW.

Principal Data of the New Industrial Triodes

Rated and maximum values			Tube type T 1000-1	Tube type T 2000-1
Filament voltage	$^{+5}_{-10}$ %	V	8·5	10
Filament current	appr.	A	26	40
Anode voltage	max.	kV	6	6
Peak cathode current	max.	A	6	12
Anode dissipation continuous	max.	kW	1	2
Grid dissipation	max.	W	75	180
Amplification factor	appr.		20	20
Frequency	max.	Mc/s	60	50
Oscillator operation with d.c. anode voltage filtered or unfiltered from three-phase rectifier				
Anode voltage		kV	5	5·5
Anode current		A	0·8	1·45
Peak grid voltage, a.c.		kV	1	1·18
Grid dissipation		W	45 (30 W reserve)	125 (55 W reserve)
Output power at the anode		kW	3·1	6·4

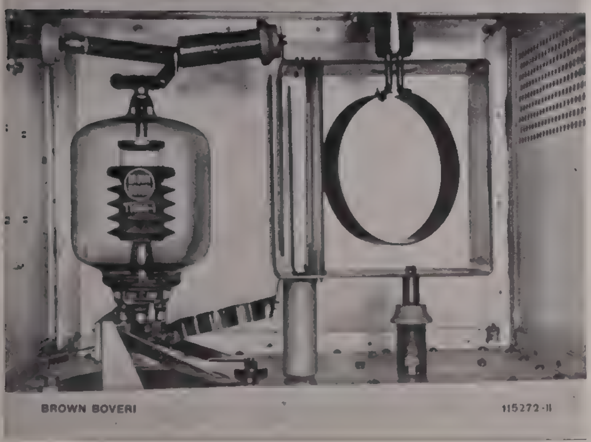


Fig. 3. – Example showing the arrangement of an r.f. generator used for dielectric welding of plastics, containing a radiation-cooled industrial triode type T 1000–1 connected as Hartley oscillator with inductive coupling. The tube oscillates at 40 Mc/s and is fed at 4 kV from a three-phase rectifier. The generator produces a power of 2 kW at the load, with an adequate reserve for fluctuation of the voltage and load. The filament voltage may vary by up to +5, —10%. Also worth noting is the simple tuning circuit on the right of the tube.

Both tubes can operate on alternating current without a rectifier, although in this case a reduction of about 35% in the output power has to be accepted.

These tubes can be used not only for industrial service, but also in communications equipment, in class B as a.f. amplifier and in class C with anode modulation up to frequencies of 50 or 60 Mc/s. In every case they are able to benefit from the advantage of requiring no elaborate, expensive cooling system.

(KME) R. HÜBNER

BRIEF BUT INTERESTING

Successful Operation of a Static Frequency Changer for 22 Years

621.314.27 (494)

AT Lütschental in the Bernese Oberland of Switzerland a static frequency changer rated 1600 kW, and consisting of a mutator with three-phase input and three-phase output, was shut down on November 5th 1960 after operating successfully for nearly 22 years. This unit was commissioned on December 22nd 1938 and was described in an earlier number of this journal.[1] This three-phase—three-phase mutator was used to

[1] C. EHRENSPERGER: The flexible coupling of systems, by means of mutators, restores his independence to the station operator, while increasing the economical operation of the systems. Brown Boveri Rev. 1939, Vol. 26, No. 4/5, p. 117–20.

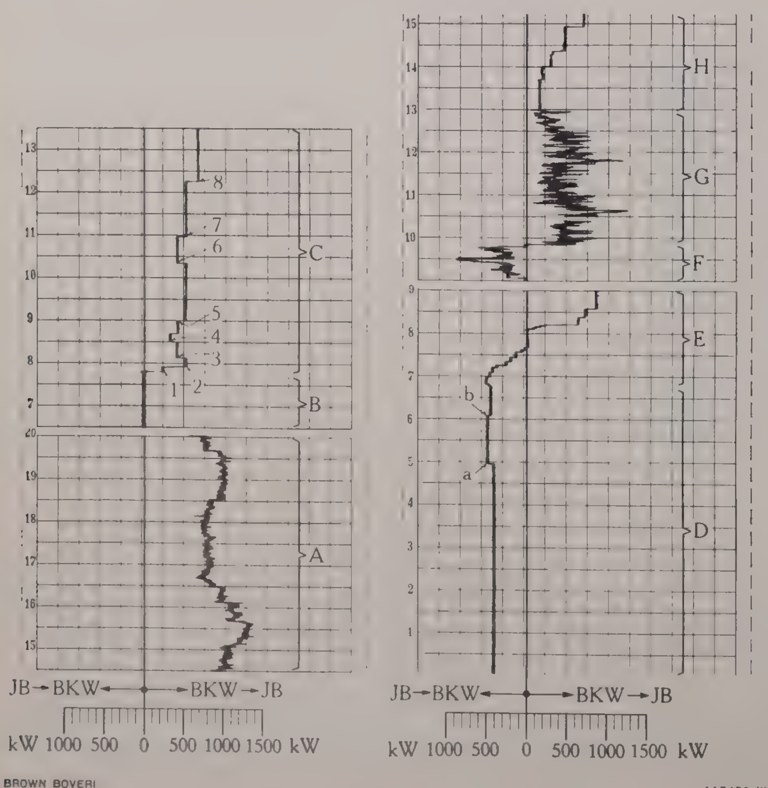


Fig. 1. – Chart of the recording wattmeter connected to the 40-c/s side of the converter, showing the exchange of power between the Jungfrau Railway (JB) and the Bernese Power Co. (BKW) under different operating conditions

A = Conversion from 50 to 40 c/s with remote manual control of the power

B = Converter out of service

C = As A, but with remotely adjusted electronic regulator. At the points 1, 2–8 the setting of the regulator was altered by hand

D = Conversion from 40 to 50 c/s. Regulator setting changed at points a and b

E and H = As C

F and G = The electronic regulator was set to maintain constant frequency in the 40-c/s system, causing the converted power to fluctuate accordingly

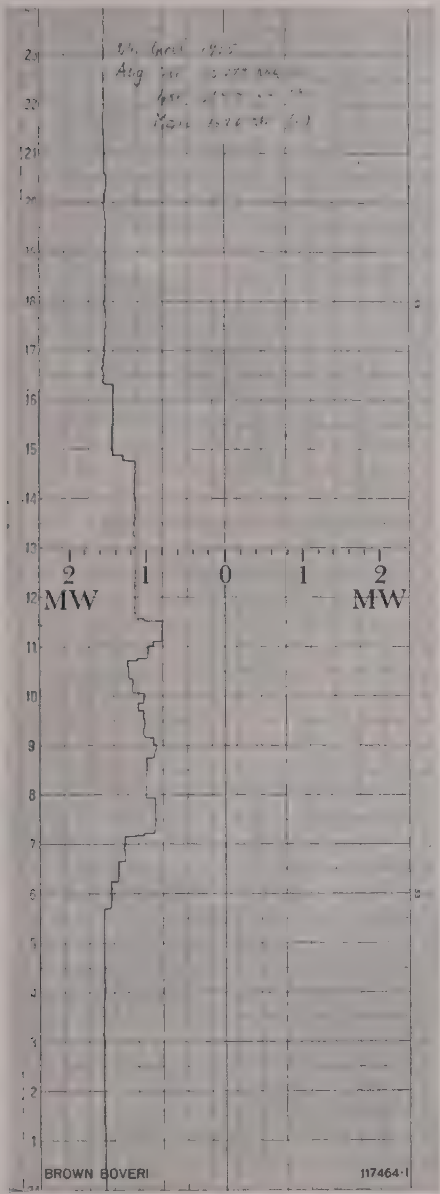


Fig. 2. – *Record of the power converted from 40 to 50 c/s on April 24th 1955*

From midnight to 5·45 am and from 4·20 pm to midnight the output was constant at 1620 kW.

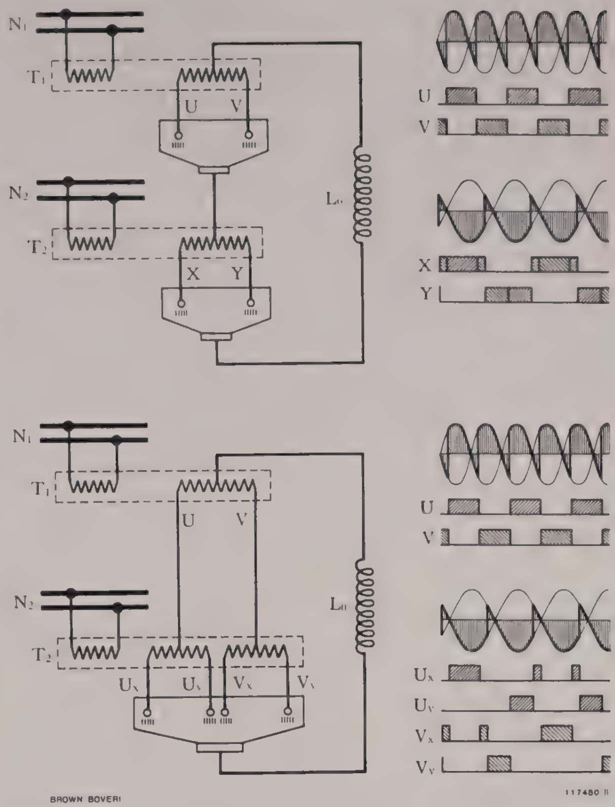


Fig. 3. – Principle of the three-phase—three-phase mutator, shown for only one phase

Top: double-converter connection
Bottom: single-converter connection

N_1, N_2 = Networks
T_1, T_2 = Transformers
L_0 = Smoothing reactor
U, V, X, Y, U_x, U_y, V_x, V_y = Anode currents

In both arrangements the currents U and V in the valve windings of transformer T_1 are identical. The currents of the valve windings of transformer T_2 are X and Y in the upper diagram. In the lower these currents are subdivided into U_x, V_x and U_y, V_y. The way in which this subdivision is performed can be seen from the diagrams on the right-hand side. The d.c. voltages shown in these diagrams can be measured separately on either side of the smoothing reactor in the double-converter connection. In the single-converter connection these d.c. voltages are intrinsic and cannot be measured. This connection represents direct frequency conversion with a single valve which, for a given voltage on the valve windings, has minimum losses.

exchange power between the 7·5-kV network of the Jungfrau Railway, with a frequency of 40 c/s, and the 16-kV, 50-c/s network of the Bernese Power Co. During traffic peaks on the railway and when insufficient water was available for the Lütschental generating station, 50-c/s power was converted to 40 c/s. At other times, surplus power from the 40-c/s system was converted to 50 c/s and fed into the Bernese Power Co. network to serve other useful purposes. The reason for shutting this station down is that the Jungfrau Railway has changed over from 40 c/s to the standard frequency of 50 c/s.

In the 22 years since it was commissioned, the mutator was effectively in operation for 5115 days (equivalent to about 14 years of continuous operation) and

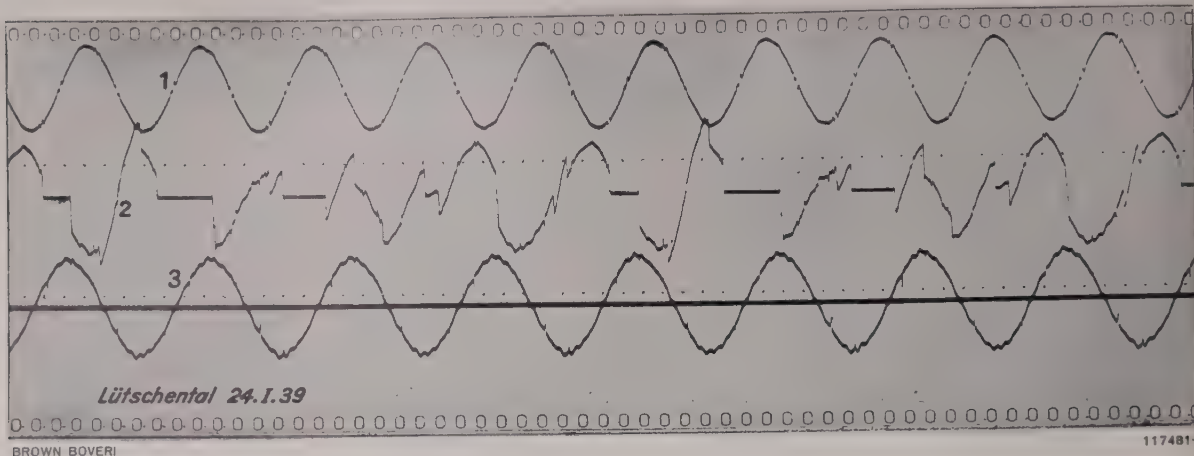


Fig. 4. – Oscillographic record of voltages

1 = 50-c/s network   2 = Voltage between one anode and cathode   3 = 40-c/s network

The voltage between anode and cathode exhibits a certain amount of superposition of the 40 and 50-c/s waves and straight-line sections, corresponding to the times during which the particular anode is carrying current, thereby indicating the slip between the two networks.

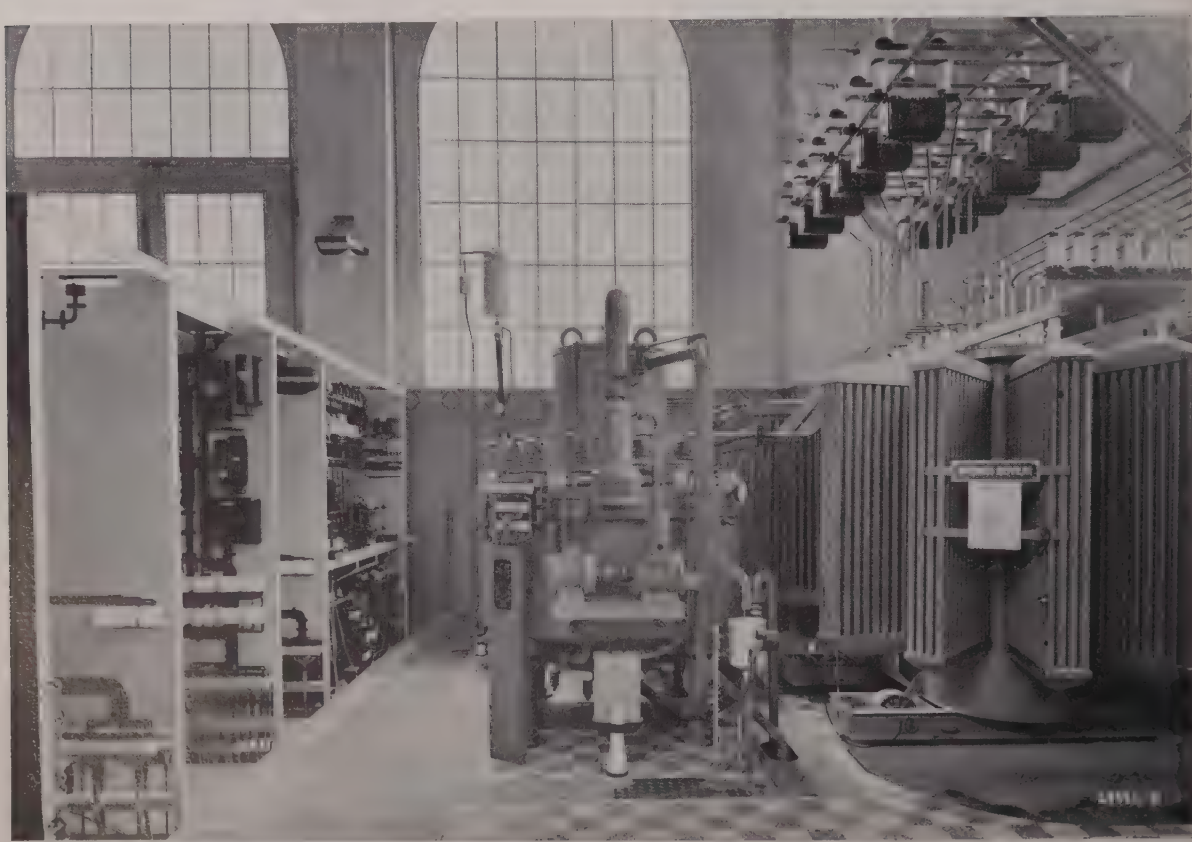


Fig. 5. – Part of the Lütschental converter station

Left to right: Control and metering gear, converter, 40-c/s transformer.

converted 114 463 700 kWh from 40 to 50 c/s, and 3 512 100 kWh from 50 to 40 c/s. The overall average efficiency, computed from the readings on the kWh-meters, was 89·5% in the one direction and 91·1% in the other. This difference is explained by the fact that the 50-c/s side was connected to a long transmission line, whereas the 40-c/s side was directly parallel to the synchronous machines in the Lütschental generating station. When the side connected to the transmission line worked as an inverter, quite a poor power factor had to be accepted on the inverter side to avoid commutation trouble, and the efficiency deteriorated under these conditions. Service interruptions were mostly due to lightning, ignoring stoppages during the initial trial period and the failure of unimportant components. The mercury-arc valve was only opened once after the first year of operation.

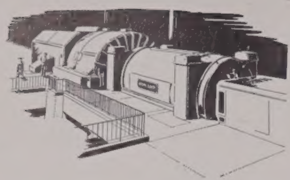
It may be of particular interest to know that this converter was automatically controlled by an electronic regulator. The power was adjusted by remote control to suit the requirements. Fig. 1 shows some typical record charts, giving the variation of the power with respect to time. At night and when no trains were running on the Jungfrau Railway, the converter was often running at full capacity, feeding into the 50-c/s network (Fig. 2). This explains why the total amount of power converted is so different in the two directions. Even though the power was sold to the Bernese Power Co. at a much lower price than that paid for the power bought from them, this exchange nevertheless provided a net surplus for the Jungfrau Railway Company.

The principle of this three-phase—three-phase converter may now be briefly explained with reference to the two diagrams in Fig. 3, both of which are shown single-phase for simplicity. At the top is the well-known double-converter connection, with the single-converter connection used at Lütschental below. In operation both are identical, the only difference being in the valve windings of the transformer T_2 and in the corresponding anode currents, shown in the diagrams on the right-hand side. A three-phase interphase transformer, to which the neutrals of the transformers T_1 are connected, is used to divide the three-phase 40 and 50-c/s systems into three independent single-phase systems, one of which is shown in Fig. 3. An important fact is that frequencies of the two interconnected systems remain independent of each other. This is sometimes referred to as 'flexible' or 'asynchronous' coupling. This can best be seen in Fig. 4, according to which the arc between one anode and the cathode burns for different intervals, depending on the phase relationship between the voltages of the two systems.

Compared with two converters in series, the single converter has the advantage of lower valve losses. The reliability of this equipment has been proved by its 22 years' service.

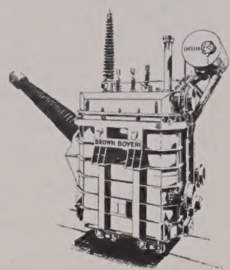
C. EHRENSPERGER

SOME OF OUR PRODUCTS



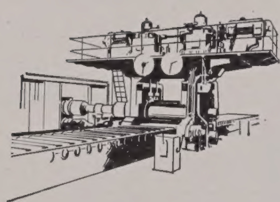
POWER GENERATION

Steam and gas turbosets; complete steam power stations; complete gas-turbine power stations, stationary and mobile; Velox boilers; alternators, protective and regulating equipment; machines and equipment for atomic power stations; switchgear; control rooms.



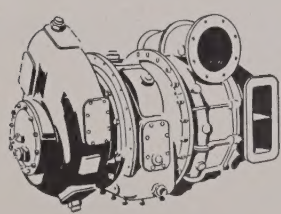
POWER DISTRIBUTION

Substations; transformers; rotating and static converters, in particular semi-conductor rectifiers; synchronous and asynchronous capacitors; switchgear installations for all voltages, using airblast, convector or magnetic circuit-breakers; metalclad drawout switchgear for high and low voltages; network protection by all kinds of relays.



POWER UTILIZATION

Electric drives and equipment for all kinds of industrial plants; variable-speed drives, fed by rectifiers or with electronic control; electric motors of all sizes and designs; industrial h.v. and l.v. switchgear; electric furnaces; r.f. generators for industrial purposes; electric boilers; arc and resistance welding equipment.

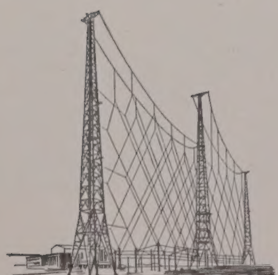


TURBO-COMPRESSORS

Turbo-compressors and blowers of axial and centrifugal design; heat pumps (Frigiblocs); exhaust-gas turbochargers for improving the output of four and two-stroke diesel engines.

TRANSPORT

Electrical equipment for locomotives, motor-coaches, trolleybuses, trams, mountain railways and ropeways; marine drives and auxiliaries.



HIGH-FREQUENCY EQUIPMENT

Transmitting and rectifier tubes; radio equipment; radio relay equipment; large transmitters; telemetering and tele-operations equipment; Thyralux dimmers.

101350

B′ B′ d.c. locomotive series 9400 of the French National Railways (SNCF)

Continuous rating 2130 kW at 50 km/h, top speed 130 km/h, weight 60 t.

The supply of control gear and the layout of all equipment for this series of locomotives, notable for the numerous innovations they contain, was entrusted to Brown Boveri's associate company in France, Compagnie Electro-Mécanique.

BROWN
BOVERI

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